

A dissertation presented by

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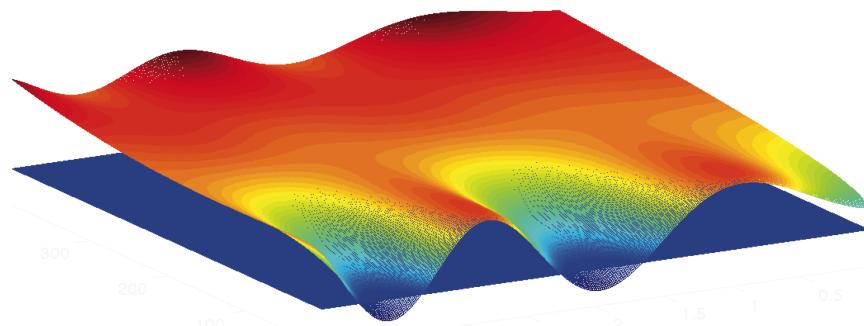
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**UNDERSTANDING THE DYNAMICS OF MOTOR LEARNING:
LEARNING FAR FROM EQUILIBRIUM**



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Foreword

This work is the support of the cited publications. Results from these three studies are presented respectively in chapter 3, 4 and 5 from the document:

Komar, J., Sanders, R.H., Chollet, D., Seifert, L. Do qualitative changes in inter-limb coordination lead to effectiveness of aquatic locomotion rather than efficiency? Accepted in *Journal of Applied Biomechanics*.

Komar, J., Chow, J-Y, Chollet, D., Seifert, L. Neurobiological Degeneracy: Supporting Stability, Flexibility and pluripotentiality in motor learning. Under revision in *Acta Psychologica*.

Komar, J., Chow, J.-Y., Chollet, D., Seifert, L. Effect of analogical instructions with an internal focus orientation in learning a complex motor skill. Accepted in *Journal of Applied Sports Psychology*.

In addition, other studies have been conducted during this research, but in order to preserve the coherence of the whole document, these ancillary works will not be presented through the present manuscript.

Seifert, L., **Komar, J.**, Crettenand, F., Dadashi, F., Aminian, K., Millet, G. Inter-limb coordination and energy cost in swimming. (*In Press*) *Journal of Science and Medicine in Sport*.

Komar J., Chollet, D., Seifert, L. How the level of environmental constraint supports neurobiological degeneracy in swimming. *Studies in Perception and Action XII*.

Komar, J., Leprêtre, P.M., Alibert, M., Vantorre, J., Fernandez, R.J., Hellard, P., Chollet, D., Seifert, L., (2012). Relationship between energy cost, swim efficiency and motor organization in elite sprint swimmers. *Human Movement Science*, 31, 620-629.

Seifert L., Leblanc H., Herault R., Button C., **Komar J.**, & Chollet D. (2011). Inter-subject variability in the upper-lower limb breaststroke coordination. *Human Movement Science*, 30, 550-565.

Seifert L., **Komar J.**, Leprêtre P.M., Lemaitre F., Chavallard F., Alibert M., Houel N., Hausswirth C., Chollet D., & Hellard P. (2010). Swim specialty affects energy cost and motor organization, *International Journal of Sport Medicine*, 31, 9, 624-630.

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INTRODUCTION

“Finding a low dimension within the dynamics of such a high-dimensional system is almost a miracle” Otto Rössler, 1987

Under an apparent simplicity as not requiring a particular attention, generating an adapted movement appears in fact relatively complex. Actually, perform a motor task is the product of relevant movements of joints, organized in time and space. Considering the large number of joints in the human motor system (10^2) and the number of muscles that organise them (10^3), one can understand the full motor complexity in performing a goal-directed activity. Indeed, human beings perform movements thanks to a neuro-musculo-skeletal system that has more available degrees of freedom than necessary to achieve a specific task. In order to quantify the level of complexity of a system, T. Ashby proposed the calculation of the *variety*, which corresponds to the number of different elements composing the system, or to the number of the different relationships between these elements, or to the different states these relationships can have (e.g. the variety of a system consisting in seven different elements connected by double-way relationships with two states each would be 2^{12}) (Ashby, 1947). If we transpose this idea to the human motor system, considering the number of state or position that an articulation can have through his numerous degrees of freedom as likely infinite, what would be the variety of this human motor system? Is it a miracle to find here a functional organization?

Previous research on motor control and learning sought to highlight how human beings can manage the complexity of the neurobiological system and the genesis of its organisation. As a psychological process, motor learning is not directly observable. Its study consists therefore in inferring based on the product of learning, that is to say based on the changes of the behaviour or of the performance occurring with practice. Numerous experiments on motor learning focused on the product of the process, namely the changes in performance outcomes, but also in terms of qualitative changes in behaviour (e.g. Chow, Davids, Button, & Koh, 2008; Liao & Masters, 2001; Nourrit, Delignières, Caillou, Deschamps, & Lauriot, 2003; Vereijken, Van Emmerik, Whiting, & Newell, 1992). Even if traditional cohort studies comparing novices and

experts can reveal the characteristics of a potential ideal coordination to reach with learning (e.g., Delignières et al., 1998; Leblanc, Seifert, Baudry, & Chollet, 2005; Temprado, Della-Grasta, Farrell, & Laurent, 1997), they are nothing other than comparisons between extreme populations, and categorized *a priori* on performances criteria. Today, the use of advanced statistical methodologies allow classifying performers *a posteriori* on the basis of actual motor patterns, and not only on performance outcomes. With the use of these statistical tools (e.g., ACP [Temprado et al., 1997], neural networks [Lamb, Bartlett, & Robins, 2011], cluster analysis [Rein, Button, Davids, & Summers, n.d.; Seifert, Leblanc, et al., 2011]), the degenerate nature of neurobiological systems have been highlighted and concepts of intra and inter variability have been revisited as they may play a functional role in motor control and learning (Davids, Bennett, & Newell, 2006; Davids, Shuttleworth, Button, Renshaw, & Glazier, 2004; Newell & Corcos, 1993). This variability may allow performers to continuously adapt to external fluctuations in the environment and by this way ensure a certain stability of the result all along the practice (Glazier & Davids, 2009a). For example, previous experiments have already shown that in achieving an identical result, different motor organizations were exhibited by participants (Hong & Newell, 2006; Rein, Davids, & Button, 2010). From this perspective, reaching perceptual-motor expertise no longer resides in acquiring a biomechanically ideal pattern called expert pattern, but rather in acquiring a pattern that is adapted and adaptable to the present constraints. This acquisition therefore would be achieved through an exploratory learning process, during which learners explore the possibilities offered by the environment and the task in order to become more attuned to them sienna (Newell & McDonald, 1994; Newell, 1991; Sporns & Edelman, 1993). Some experiments have investigated this exploratory process through the non-linear pathway of the temporal dynamics of behavioural changes during learning. For instance on a ski-simulator task, the transition from novice to expert has been defined by a period of intermittency between different behaviours, leading to the stabilisation of an expert pattern (Delignières, Teulier, & Nourrit, 2009; Nourrit et al., 2003; Teulier & Delignières, 2007). Nevertheless, it seems like there is not a unique way in behavioural changes during learning, namely that the nature of the transition may be dependent on the interaction of constraints acting on the learner during the practice (i.e. constraints linked to the environment of the practice, the task itself or the learner's characteristics [Newell, 1986]). The less the environment or the task appear constraining, the more the learners are able to freely explore all the

possibilities offered by the task, and conversely. Therefore, the weight of the constraints may influence the duration of learning and the nature of the pathway to reach expertise (e.g. duration of the transition, gradual or abrupt nature of the transition, existence of multi- or meta-stability during the process). From this perspective, the design of an optimal set of constraints may not be viewed as directly *causing* a movement, but rather as *guiding* the learner through all the possibilities of the workspace. Actually, an important literature has focused on the nature of the information given to the learner during the practice, showing that this information can play a paramount role in reaching high performance. For instance, a skill implicitly acquired appears longer to acquire, but also more resistant while facing stress, pressure or else fatigue (Lam, Maxwell, & Masters, 2009a; Masters, 1992, 2000; Shea, Wulf, Whitacre, & Park, 2001; Steenbergen, van der Kamp, Verneau, Jongbloed-Pereboom, & Masters, 2010). In the meantime, the allocation of the information (i.e. internal or external focus) can lead to different effect of learning, both in terms of performance outcome as well as in terms of movement form (Lohse & Sherwood, 2011; Uehara, Button, & Davids, 2008; Wulf, Höß, & Prinz, 1998; Wulf, Lauterbach, & Toole, 1999; Wulf, McConnel, Gärtner, & Schwarz, 2002). However, these studies on internal/external focus of attention did not focus on the pathway of acquisition. Interestingly, the study of the dynamics of learning might inform about the beneficial aspect of different types of focalisation on exploratory behaviours.

In view of this short state of the art, the general aim of this thesis will be to question: i) the existence in swimming of a biomechanical effective movement pattern. Specifically, the high level of forward resistance due to the aquatic environment makes the chronometric performance in swimming highly dependant on the movement pattern. In this context, is the degenerate nature of neurobiological system always verified? ii) the existence and necessity of an active exploration during learning, therefore the existence of non-linear transitions between the initial behaviour and the to-be-learned pattern. Do the high level of environmental constraint in swimming and the existence of a specific effective pattern influence the duration and/or nature of the exploration? iii) the paramount role of verbal instructions as temporary constraints in guiding the explorative behaviours. The question refers to the relevance of proscribing some area of the perceptual motor workspace (i.e. provide boundaries to the exploration) rather than prescribing a specific to-be-learned

pattern.

In order to answer this questioning, the present work is structured around three main parts. In the foreword, the principles of an ontology of complexity that guide our research will be presented. This positioning will be followed by a presentation of tools and concepts unified in an Ecological Dynamics approach to motor control (Araújo, Davids, & Hristovski, 2006). This part will focus on the degenerate nature of neurobiological systems and on the functional role of motor variability. An overview of the current knowledge on motor learning will follow the first part on motor control. This second part will focus on the exploratory process occurring during motor learning and the possibility to guide this exploration with manipulating interacting constraints. A particular point will focus on the importance of verbal instructions used as temporary constraints in order to guide exploration; more precisely, how the implicit nature and the allocation of the information delivered during the practice can guide the exploration and modify the outcome of the learning process.

Based on this presentation, the personal contribution will include two studies examining the nature of the expert pattern of coordination and the expression of neurobiological degeneracy in the relation between stability and flexibility of the coordination. From these previous results, a study will question how the respect of a *non-linear pedagogical approach* (Chow et al., 2006; Chow, Davids, Hristovski, Araújo, & Passos, 2011) may influence the nature of the verbal instructions in order to favour the search of optimal solutions during learning. The last experiment will specifically focus on the temporal dynamics of the coordination during the learning process. The comparison between different learning conditions will argue for the respect of a non-linear pedagogical approach respecting learner's intrinsic dynamics and interacting constraints. A last part will conclude through a general discussion of the results and scientific and practical contributions of the thesis.

Ontological position

As early as 1938, G. Bachelard noted the need for an epistemological break with the past in order to move from “ready” explanations (i.e., common sense) for a phenomenon that arose from habit or conditioning to an understanding based on scientific theory and approaches (Bachelard, 1971). Such a move required the use of instruments, scientific methods, and a certain world view. The ontological proposition that undergirds this work is complexity, or the notion that humans, like all other life forms, are complex systems.

According to von Bertalanfy, a complex system is a set of units in mutual interrelationship. De Rosnay adds that a system is a set of elements in dynamic interaction, organized around a goal. Even though no single definition is unanimously agreed to, living systems are undeniably complex (from com-plexus, the property of something that is woven together) (Durand, 1979). In this sense, it is not so much the high number of elements that signify complexity, but rather the many relationships between them.

Emergence. These relationships therefore make a complex system indivisible, and complexity thus inevitably evokes the notion of globality. Globality implies that a complex system, although composed of separate elements, cannot be reduced to the mere sum of these elements. Atlan (1979) therefore contrasts "complicated" and "complex" by noting that a complicated system can be easily understood by breaking it down into its component parts, whereas a complex system exhibits new properties at the global level. Von Bertalanfy (1969) may have been the first author to explore the notion of a system as a whole that cannot be reduced to its parts, which led to the idea that qualities, or properties, emerge from the system that cannot be found in the individual parts. Thus, a system may be more than the sum of its parts (e.g., "the cells of a cat do not chase the cells of the mouse" [R. Thouvarecq]), but it should be noted that it also may be less than the sum of its parts (De Rosnay, 1975; Fortin, 2005). From this standpoint, the study of complex systems requires more than the holistic vision announced by Zwirn (Zwirn, 2006), as it requires both a holistic and macroscopic vision focused on the “whole” phenomenon and a microscopic vision focused on the parts—with the understanding that either vision alone is inadequate for

full understanding. The idea of globality, which is strongly tied to the notion of systems and their relationships, is thus a fundamental and particularly powerful concept for uncovering a primordial characteristic of systems: emergence.

Self-organization. Conversely to the assumptions of classic reductionist science, element A and element B are not necessarily related causally, as in “A has an effect on B.” The relationship implies both A affects B and B affects A. Depending on the level of analysis, this interrelation can be seen to arise at different levels (Morin, 1990) (e.g., neurobiological, behavioral, social, etc. [Mason, 2010]), but in all cases the idea of interrelationship implies that the relationship between elements is not linear but circular. A circular relationship refers to a certain idea of organization that describes the arrangement of the relationships between the individuals or components of a system in such a way that the system produces new qualities that are individually lacking. Organization is the process by which matter, energy, or information is assembled and then implemented or put into a form (Morin, 1990). This process can be driven by the system itself without prescription from a higher-order system, and in this case it can be said to be self-organizing. Self-organization is in this sense both a process and a state. In an open complex system (according to Morin, in order to survive every living system is open to wider systems operating at other levels, with which it can exchange energy [Morin, 1990]), self-organization is an ongoing process that maintains a state of organization.

Dynamic stability. This inexorable opening of a complex system reflects the idea of the disentropy, or the balance between entropy and negentropy (Morin, 1990, taken from Schrödinger, 1944), between determinism and randomness. This idea perfectly defines the notion of chaos in that it refers more to the management of complexity than to its complete elimination. Any open complex system achieves a stable state through a process of dynamic stability, which results from the ongoing exchanges among the system components and with the environment. Stability is ensured by a constant flow of energy, consisting of the exchanges of information between the system and its environment (Haken, 1983). These complex systems in constant interaction with their environment are called dissipative dynamical systems (Prigogine, 1994). Morin (1977) refers to self-organized eco-systems to highlight the close circular relationship that a complex system maintains with its environment while remaining self-organized.

Sensitivity to initial conditions. The notion of the dynamic stability of a system in constant contact with the environment is directly related to the chaotic aspects of

complex systems. This chaos, which can be called "deterministic chaos," refers to the order that lies hidden behind apparent disorder and is the system's state of organization, which is a stable state. But this order is quite relative because imperceptible changes can tip it into disorder or into another state of order through a *sensitivity to initial conditions*, commonly known as the butterfly effect (Lorenz: the beating of a butterfly's wings in Brazil can set off a tornado in Texas") (Gleick, 1987, p. 44).

Nonlinearity. Indeed, this sensitivity to initial conditions brings out the characteristic of the unpredictability of a complex system, in the sense that there can be no proportionality between the observed effect and the cause. Thus, the complex systems that exhibit deterministic chaos appear to be indeterminable (Lorenz noted in 1963 that acceptable weather forecasts will never extend beyond 4 or 5 days regardless of the technology; Gleick, 1987). In other words, a slight modification in the environment can have a significant impact on system behavior. Therefore, the only way to study a complex system is by studying its changes over time or by modeling (Zwirn, 2006).

Transitions. More generally, complex biological systems may exhibit behaviors that are both stable and flexible. This suggests transitions from one state of organization to another, which is in fact considered to be an emergent property of complex systems (Prigogine, 1994). Under environmental influences, a stable state of organization may transit to another such state or even to a state of disorganization. Beyond a certain threshold of organization between the system elements—a "critical state"—the whole system collapses into a temporary state of disorganization while it reorganizes itself into another stable state (Bak, 1996; Clergue, 1997). A classic example is the transition between laminar and turbulent water flow in a river. The more the liquid flow rate increases, the more the Reynolds number increases, and the flow rate will cause the system to abruptly shift from a laminar state (a) to a turbulent state (b) when the Reynolds number exceeds the critical value of 2040 (Avila, Moxey, De Lozar, Barkley, & Hof, 2011). The relevance of the critical state theory is also illustrated by a sandpile (Bak, 1996): we can keep adding grains of sand to a pile without anything happening, but at a certain point, a single grain will trigger an avalanche and the pile will eventually stabilize at a height well below the threshold that triggered the avalanche. In fact, despite the high number of grains affected by the collapse, we see that the global dynamics of a complex and nonlinear system come

down to a few key parameters such as the height of the pile and its base circumference (Bak, 1996).

Motor learning shows all the characteristics of these *nonlinear* dynamical systems whose behavior we cannot accurately predict. One grain of sand too many, but we do not know when or which one will cause the collapse of the sandpile, just as one new piece of information may help to rebuild an entire section of knowledge and trigger an abrupt rupture in a behavior or performance, with a *transition* from a "beginner" *stable state* to one that is more "expert." From this point of view, learning can be summarized as system evolution, in the sense that evolution is the "capacity of a system to change its internal structure, its (*self*) *organization*, in a durable way so that its behavior is more in line with the environment" and new behavior *emerges* (Zwirn, 2006, p. 135). Our theoretical approach is thus based on the ontology of complexity. The general idea is to consider humans as complex neurobiological systems composed of a multitude of components (e.g., joints, muscles, tendons, etc.) and levels of interaction (e.g., neural, behavioral, social, etc.) that will coordinate according to the principle of self-organization.

Theoretical Framework

Chapter 1 : Dynamical approach to motor control

Notwithstanding the undeniable scientific power of linear approaches [Shea & Wulf (2005) report 782 citations of Schmidt (1975)¹ between 1975 and the end of 2004] and, more generally, Cartesian determinism, an alternative view that is rooted in an epistemology of complexity has developed through an approach called *Ecological Dynamics* (Araújo et al., 2006; Brymer & Davids, 2013; Davids, Araújo Hristovski, Passos, & Chow, 2012; Davids, Button, & Bennett, 2008; Vilar , Araújo, Davids, & Button, 2012). This framework integrates the concepts and tools of both *coordination dynamics* (Kelso, 1995) and *ecological psychology* (Gibson, 1979). Thus, the concepts and tools of the so-called biophysical approach to human behavior (Haken, 1983) are included in the ecological dynamics approach (Davids & Araújo, 2010). As such, this approach focuses on identifying the signatures of dissipative dynamical systems through the study of the neuromusculoskeletal system (Kelso, 1995) and the effects of constraints on the emergence of the spatio-temporal order: coordination (Newell, 1986). In addition to a focus on this emergent property of behavior, this approach builds on the work of Gibson (1979), who posited that individuals relate to their environment by direct informational coupling without the mediation of symbols (Shaw, 2003).

The ecological dynamics approach reveals the inherent foundation of the complexity paradigm in the sciences. It calls into question the foundations of linear approaches, such as the role of information, symbolic representations, the need for movement prescription, the balance between causes and consequences of movement, and the mediation of symbols in the relationship of individuals with their environment. More generally, it questions the notion of a pre-constructed physical world (and thus independent of the subject) that only needs to be decoded. Behind the common reluctance to evoke cognitive constructs as mediating perceptual-motor

¹ The schema theory (Schmidt, 1975) is probably the most known linear model in sport sciences research, even if there exist some other models (e.g. computational model from Wolpert et al., 2011).

processes, both approaches agree on the main position that the study of perception and action is advanced by an analysis of the recognition (perception) and formation (action) of higher-order collective invariants or variables (Beek, Jacobs, Daffertshofer, & Huys, 2003).

The problem of degrees of freedom : the challenge of coordination

Pattern generation in neurobiological systems

To address the problem of how multiple degrees of freedom are organized in the human body, N. Bernstein (1967) referred to *synergies* that make the control of a complex neurobiological system possible. However, from a purely anatomical point of view, synergy is essentially a specific arrangement of the agonist and antagonist muscles in joints. Conversely, from a functional point of view, it suggests the relationships between muscles in a behavioral situation; that is, when the muscles are united in a common goal (Gel'fand, Gurfinkel, Tsetlin, & Shik, 1971; Haken, 1983). From this perspective, synergy occurs when an error created by a component of a system organized for a specific purpose is compensated by a change in the implication of the other components in order to ensure task completion (Latash, Scholz, & Schöner, 2002).

According to Kelso (1995), synergy is both the external language of movement and the internal language of the nervous system. When the external facet of synergies is studied, other terms are used, although all have in common a focus on the functional side of the concept of synergy (Turvey, 2007). For example, Tuller, Fitch & Turvey (1982) used the term *coordinative structure*, Balasubramaniam & Turvey (2004) used *coordination mode*, and Zanone & Kelso (1992) used *coordination pattern*. In fact, this raises the problem of finding a term that conveys the notion of the many initially relatively independent degrees of freedom temporarily behaving as a single functional unit (Turvey, 2007). In this manuscript, the term coordination pattern or simply coordination will be used to refer to this synergistic phenomenon.

Kugler et al. (Kugler, Kelso, & Turvey, 1980) define coordination as "a group of muscles that often extends over several joints forcing them to act as a functional

unit." More specifically, a coordination pattern can be seen as a function that organizes the initially independent elements of a system into a functional unit in time and space (Newell, 1985, 1996). The formation of such coordination thus resolves the problem of the great complexity of the neuromusculoskeletal system due to its many degrees of freedom. These degrees of freedom correspond to system elements that may vary independently of each other. A major feature of this coordination is *self-organization*, which means that the organization occurs without the involvement of an external control unit. The state of order or organization of the neuromusculoskeletal system *emerges* from the set of all the elements based on the principle of self-organization. The "system organizes itself, but there is no 'it,' no internal system agent requiring the organization" (Kelso, 1995, p. 8). Therefore, no preformed program stored in memory is needed to guide the development of this coordination. As a result, the conversion of independent system elements into a functional unit simplifies and makes control possible. The set of all the degrees of freedom thereby regulated is compressed into a few meaningful degrees (Schöner & Kelso, 1988a).

The study of motor coordination is thus at the heart of the *dynamical approach to coordination* (Kelso, 1995), with the goal being to understand the laws, principles and mechanisms that govern how patterns of coordination emerge in time and space (Jantzen, Oullier, & Kelso, 2008; Kelso, 1995). Coordination has been studied at different levels of analysis, from the brain to social interactions. Studies have focused on the coordination among the joints of the same limb (Kelso, Buchanan, & Wallace, 1991), between limbs (e.g., Kelso & Jeka, 1992; Kelso & Schöner, 1988), between an individual and the environment (Fink, Foo, Jirsa, & Kelso, 2000), and among several interacting individuals (Esteves et al., 2012; Issartel, Marin, & Cadopi, 2007; Oullier, de Guzman, Jantzen, Lagarde, & Kelso, 2008; Vilar et al., 2012). For example, Issartel et al. (Issartel et al., 2007) showed that once two people share the same visual information, they have a strong tendency to coordinate their movements, even when their intention is to desynchronize them. Also, recent dynamical investigations of the relationships between neurons or brain regions have suggested similarities with the processes of formation and governance of motor coordination (Carson & Kelso, 2004; Fuchs, Jirsa, & Kelso, 2000; Jantzen et al., 2008). These studies highlight the idea that coordination is not related to the material properties (e.g., muscles, neurons, individuals), but to the relationship among these elements (Kelso, 1995).

The study of coordination dynamics and the relationships between the different levels of analysis have facilitated the investigation of many sports such as

football (Chow, Davids, Button, & Koh, 2008), basketball (Rein et al., 2010), horseback riding (Lagarde, Kelso, Peham, & Licka, 2005), tennis (Palut & Zanone, 2005), swimming (Chollet & Seifert, 2011), and simulator skiing (Feeds et al., 2003). Clearly, the emergence of order from apparent disorder through a coordination pattern is a key element regarding the organization of degrees of freedom in the neurobiological system. The study of this coordination is primarily through its evaluation, through the recognition of an *order parameter* that can capture all its complexity.

Order parameter. The study of coordination is in part the "ability to recognize the meaningful informational unit of movement" (Greene, 1971, p. 18, in Saltzman & Kelso, 1987). This informational unit, called the order parameter, is a collective variable because it reflects the coordination of many factors. The interest of an order parameter in the study of coordination is that the number of states of this parameter at a global level is much lower than the number of states that can be defined for the independent components (Kay, 1988). This parameter is thus defined as *macroscopic*, because it summarizes the emerging aspect of coordination in a single value, and as *qualitative*, because it reflects the couplings among the elements of a system, or the dynamics of these couplings.

The determination of the order parameter that reflects the macroscopic level of coordination is the first step in studying coordination (Kelso & Schöner, 1988). Thus, several tools have been used to assess coordination in motor tasks: cross-correlations, relative phase, and vector coding (Glazier & Davids, 2009b; Wheat & Glazier, 2006). Cross-correlations indicate the type of relationship between body segments (in-phase or antiphase), the degree of linking between these segments and, when the measurements are repeated, the stability of the coordination pattern (Temprado et al., 1997). However, the calculation of the relative phase (ϕ) is generally preferred because it reflects the spatial and temporal relationships between joints (Kelso, 1995; Varlet & Richardson, 2011).

The relative phase has probably been the most often calculated order parameter in coordination studies. The paradigmatic work in the field of motor coordination has thus focused on the timing of the indexes of oscillation movements (Kelso & Schöner, 1988; Kelso, 1984) using the discrete and continuous relative phase between the two index fingers as the order parameter. Based on this work, the relative phase has been used as the order parameter in many coordination studies, including the study of postural coordination, for which these two modes of

coordination (in-phase and antiphase) have also been advanced (Bardy, Marin, Stoffregen, & Bootsma, 1999; Bardy, Oullier, Bootsma, & Stoffregen, 2002). Indeed, in a task of tracking the oscillations of a target, the relationship between the ankles and hips of subjects show in-phase coordination (i.e., simultaneous flexion or extension) or antiphase coordination (i.e., hip flexion associated with ankle extension or vice versa).

Whatever approach is thought best to define the dynamics and the nature of an order parameter, the objective is always to define the typical behavior of the system. Among the infinity of coordination modes that can be used to achieve a specific task, the order parameter generally defines a limited number and can thus be called the *preferential coordination* or *attractor*. For different initial conditions (e.g., a phase shift of 60° between the two index fingers), a convergence in the values of the order parameter occurs over time toward an attractor.

Between stability and loss of stability. Bimanual coordination generally shows two attractor states, the in-phase ($\phi = 0^\circ$) and antiphase ($\phi = 180^\circ$), although in-phase coordination appears more stable than antiphase (Kelso, Scholz, & Schöner, 1987). This situation of two stable attractor states is the most basic form of *multistability*, bi-stability. Multistability is the coexistence of multiple stable states for exactly the same practice conditions (Kelso, 1995). In their study of the quadrupedal gait of horses, Hoyt & Taylor (1981) showed that at certain speeds, the horses were capable of bi-stability (e.g., they were able to trot or gallop at 4-5 m.s⁻¹), while at other speeds, they exhibited mono-stability (e.g., they were only able to trot at 2.5 m.s⁻¹). Figure 1.A further illustrates this concept of bi-stability in visual perception. In fact, the same pattern (Figure 1.A) can be seen as a cube oriented toward the left (Figure 1.B) or as a cube oriented toward the right (Figure 1.C) (Tschacher & Haken 2007).

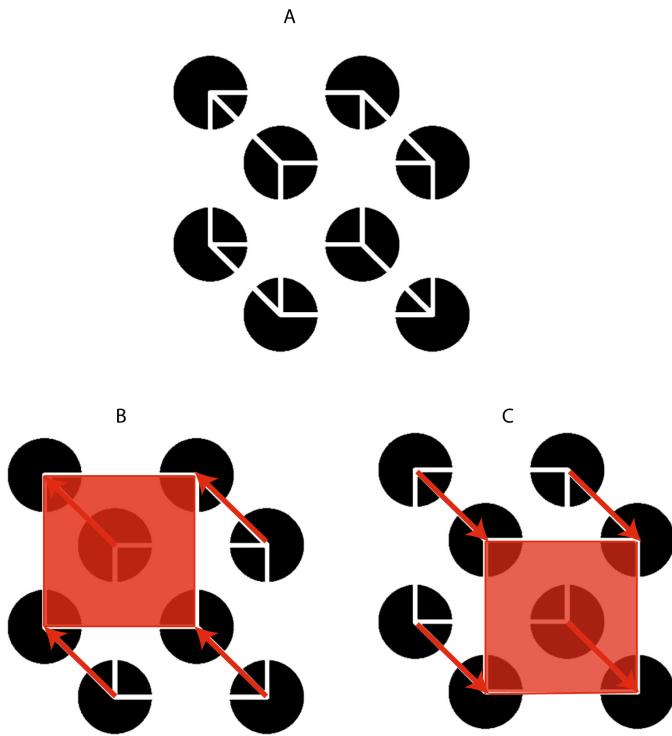


Figure 1. A variant of the Necker cube (A), which can be perceived as oriented in three dimensions in different ways (B or C). (Adapted from Tschacher & Haken, 2007, p.5).

Similarly, in studies on inter-limb (arm-leg) coordination, four attractors have been identified for low oscillation frequencies, namely the jump, step, bound and trot (Jeka, Kelso & Kiemel 1993; Kelso & Jeka, 1992; Schöner, Jiang, & Kelso, 1990). Conversely, when the oscillation frequency is higher, certain arm-leg coordination patterns are no longer feasible, i.e., at high frequency (generally greater than 2.5 Hz), arm-leg pairs no longer exhibit an antiphase pattern, but only in-phase (Kelso & Jeka, 1992). This phenomenon of multistability is also illustrated by the principle of the Coexistence of Equally Valid Alternatives (CEVA) and is defined on the basis of a stability criterion (Kelso, 2002, p. 368). Generally, stability is measured by the inter-cyclic or inter-trial standard deviation of the relative phase and corresponds to the *critical fluctuations* (Kelso & Jeka, 1992; Schöner, Haken, & Kelso, 1986).

Critical fluctuations. The state of a system is said to be stable when the fluctuations are small²: it is an attractor. Conversely, when these fluctuations increase significantly, the state of the system becomes less stable. For example, Short et al. (2002) showed greater fluctuations in the antiphase coordination mode, confirming

² With reference to the definition of complex systems, these fluctuations never entirely disappear in living systems, and one can find here the idea of dynamical stability (Bak, 1996; Clergue, 1997)

that this mode is less stable than in-phase. In addition to the nature of the coordination, other parameters influence stability. In their experiments on multi-joint coordination with the MAC system, Jeka & Kelso (1992) showed that coordination requiring movement in the same direction (iso-directional) appears more stable than coordination that requires movements in the opposite direction (i.e., iso-contraction), this being more striking when the coordination is contralateral (e.g., left arm-right arm). The authors concluded that the stability of multi-joint coordination is governed more spatially than anatomically (Kelso & Jeka, 1992). The study of Baldissera et al. (1991) confirmed this hypothesis, showing that the coordination between the wrist and ankle is more stable when the movements are iso-directional than when they are not.

Relaxation time. When an attractor loses its stability, the time it takes the system to return to a stationary state is called the *relaxation time* (Scholz & Kelso, 1989; Schöner et al., 1986.). Thus in bimanual coordination, a 50-ms resistance was applied during oscillations but only on the right index finger to cause a temporary disruption in the coupling of the two index fingers (Kelso et al., 1987). The authors showed that the time to return to the initial coordination depended on the stability of the initial coordination. More specifically, the relaxation time was greater for antiphase (about 600 ms) than for in-phase (about 400 ms). In addition, this relaxation time appears to be even greater (1300 ms) as a critical state approaches (*critical slowing down*) (Schöner & Kelso, 1988a). This critical state corresponds to an area of *bifurcation* of the state of the system, also called the phase transition (Haken, 1983; Kelso 1984, 1995).

Phase transition. When the destabilization of one attractor leads to the stabilization of another, this is called phase transition, or bifurcation. Phase transition is the spontaneous shift from one state to another (Haken, 1983). A key feature is the significant loss of stability in the relative phase (i.e., higher critical fluctuations) around this transition. Variability thus appears to be inherent to changes in coordination (Van Emmerik & Van Wegen, 2000). In bimanual coordination, when the oscillation frequency was gradually increased (from 1.25 to 3.5 Hz), the relative phase spontaneously changed from the initial antiphase to in-phase, thus showing high frequency in a single behaviour: in-phase coordination (Kelso, 1984). The time to pass from one attractor to another is called the *transition time* (Schöner et al., 1986). Generally, the transition time seems longer when the transition is from a more

stable state to one that is less stable and shorter when from a less stable state to one that is more stable (Kelso, Scholz, & Schöner, 1988).

Control parameter. Discontinuous phase transition is characterized by a sudden and abrupt jump between two modes of coordination (Van Emmerik & Van Wegen, 2000). This phase transition is nonlinear, in the sense that a sudden and abrupt change in the order parameter occurs from the continuous variation in the *control parameter*. The control parameter is non-specific because it induces a change in coordination without precisely defining it. In bi-manual coordination, the oscillation frequency is a control parameter that abruptly switches antiphase coordination to in-phase at a frequency of about 2.25 Hz (Kelso, 1984). Similarly, in their study of the walk-run transition, Diedrich and Warren (1995, 1998) showed that when walking speed increases, an abrupt transition occurs between the pattern of walking and running at around 2.07 m.s^{-1} .

Hysteresis. These authors also emphasized hysteresis, the effect of history on the phase transition. When the control parameter (i.e., walking speed) increased, the walk-run transition occurred at an average speed of 2.05 m.s^{-1} , whereas when the speed decreased, the transition occurred at 2.09 m.s^{-1} (Figure 2) (Diedrich & Warren, 1995). More generally, hysteresis refers to the tendency of an attractor to remain in its current state when the direction of the control parameter changes, thus delaying the transition (Kelso, 1995).

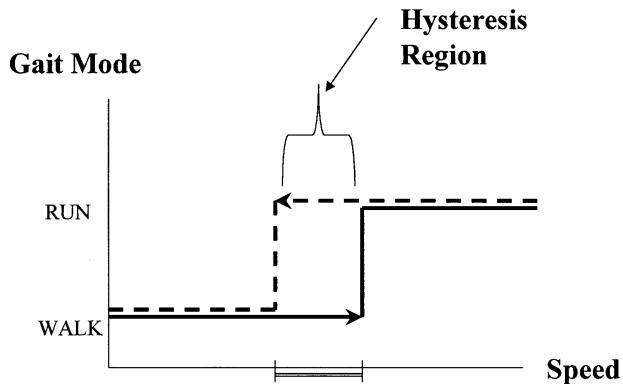


Figure 2. Example of hysteresis in the walk-run transition (dotted line for the run-walk transition and solid line for the walk-run transition) (Van Emmerik & Van Wegen, 2000).

In fact, the authors demonstrated that the type of transition observed in the walk-run transition led to the coexistence of two concurrent attractors (i.e., that of walking and that of running) in the transition region (i.e., speed of 2.07 m.s^{-1}), both of which are relatively unstable (Figure 3).

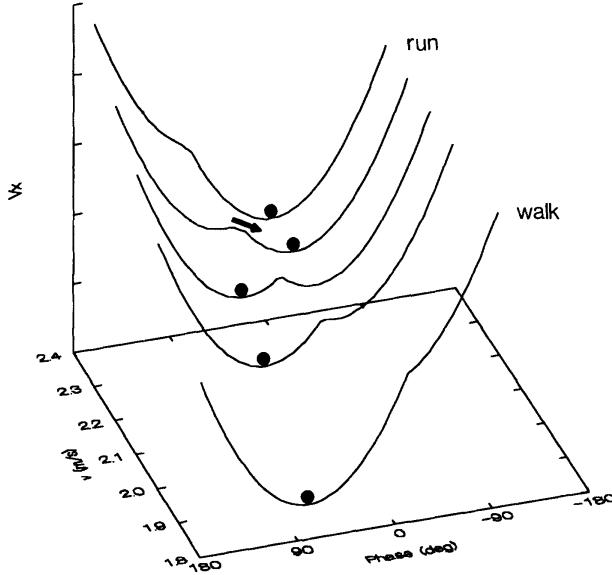


Figure 3. Schematization of the attractor landscape for the walk-run transition. With increasing speed, the system moves from walking (relative phase of 90°) to running (relative phase of -90°) through an unstable region where the two attractors, walking and running, show the same stability (Diedrich & Warren, 1995).

This type of transition is characterized by a progressive fusion between the attractor and repeller, causing a drift in the stability of the attractor before the transition, without, however, there being an intermediate state between one stable pattern and another (Diedrich & Warren, 1995; Jeka et al., 1993.). Thus, in this case and, more generally, in cases of *relative* coordination, the phase transition is similar to a *saddle-node* type of transition, with the coexistence of two relatively unstable states during the transition (Kelso & Jeka, 1992). In contrast, Buchanan et al. (Buchanan, Kelso, De Guzman, & Ding, 1997) showed that the transition between two coordination patterns does not always occur abruptly from one attractor to another. Unlike index-finger oscillation tasks in one dimension (i.e., horizontal), these authors showed that a spatial transition can be effected by moving the fingers in different planes. These spatial transitions in two dimensions (i.e., horizontal and vertical) can take place abruptly or gradually (by a supercritical Hopf bifurcation). In other words, when the recruitment or elimination of degrees of freedom is possible, the transition is

not always abrupt. In this case, the change is always nonlinear, but some intermediate states can occur during the transition (Figure 4).

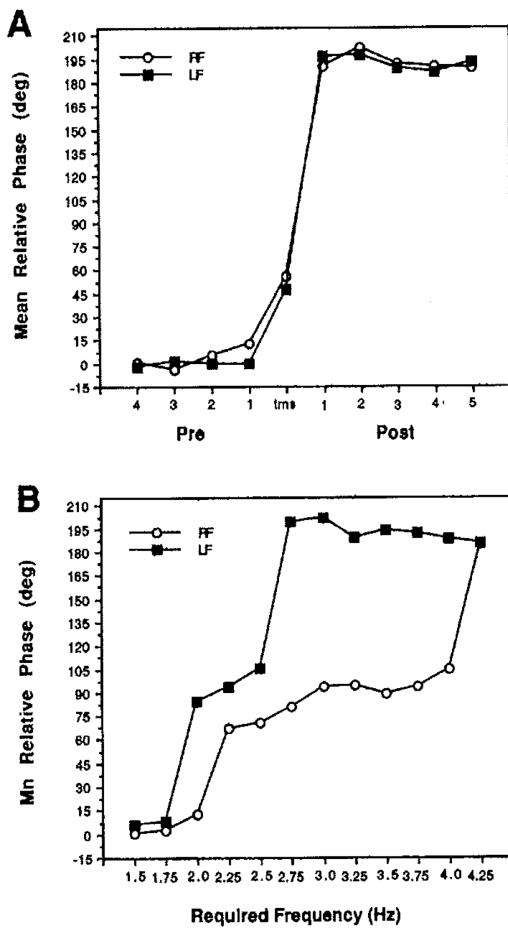


Figure 4. Representations of an abrupt transition (A) and a gradual transition (B) in index-finger oscillation tasks (Buchanan et al., 1997).

The emergence of interacting constraints

To carry out a motor task, the motor system must be coordinated under the influence of *internal* neuroanatomical forces and the external *environmental* forces that act on the individual (e.g., gravity, buoyancy, room temperature) (Bernstein, 1967). From this perspective, stable coordination patterns are not stored by the central nervous system, but rather they emerge from these forces, or constraints (Newell, 1986). Constraints are defined by Newell (1986) as the limitations or restrictions on all the possible configurations of the neuromusculoskeletal system. Instead of prescribing a specific coordination pattern to adopt, constraints impose nothing but they do channel behavior. A particular aspect of these constraints is that coordination

stability can be altered by the constraints imposed on the individual. Newell (1985, 1986) thus defined three categories of constraints³ that act on and channel behavior: environment, task and organism.

Environmental constraints refer to the physical variables found in the natural world, such as gravity, ambient temperature, and brightness. Other environmental constraints may be social factors like peer pressure, family support and cultural norms (Haywood & Getchell, 2005; Reed & Bril, 1996). For example, the quality of the support surface in postural coordination tasks is an environmental constraint. The specificity of the aquatic environment arises from the impact of buoyancy working against the force of gravity and the strong resistance to forward movement because of the high density of water.

Task constraints are generally more specific to a particular context of performance than environmental constraints. These include the goal of the activity, the rules regulating it, the necessary equipment, and even the information sources for the performance context. For example, the weights of tennis rackets and ice-climbing axes, the regulations for swimming strokes, and the number of players per team for a rugby match are all task constraints.

Organismic constraints refer to the individual's characteristics. They may be structural (e.g., height, weight), functional (e.g., fatigue), or related to personal history, previously acquired knowledge, and motor skills. According to Bingham (1988), this type of constraint refers to the constraints inherent to the neuromusculoskeletal system, as opposed to the incidental constraints defined by tasks and/or the environment.

It would nevertheless be an error to think that only constraints, or only a single type of constraint, could explain the emergence of coordination. Indeed, coordination emerges not from a selection or addition of constraints, but rather from the interaction of the many constraints that are continuously acting on the individual (David et al., 2008; Guerin & Kunkle, 2004; Newell & McDonald, 1994; Newell, 1986). It sometimes even seems difficult to distinguish between the types of constraints. For example, in swimming, the changes in swimming speed (swimming at $\approx 1.5 \text{ m.s}^{-1}$ then 2 m.s^{-1}) are variations in an environmental constraint in that increasing the speed

³ Even if other types of categorization exist (Warren, 2006, defines physical constraints and informational constraints), the taxonomy from Newell (1986) seems to be the one that most contributed to the comprehension of the effect of interacting constraints.

causes an exponential increase in the resistance to forward movement. In contrast, changes in the pace [swimming at 75% of maximum speed (1.5 m.s^{-1}) and then at 100% (2 m.s^{-1})] is a variation in a task constraint because in this case the amount of resistance to forward progress is not defined, but rather the task that the swimmer must perform. In addition, the constraints acting on behavior are more often temporary than permanent, and their influence can be strengthened or diminished according to the time scale (Guerin & Kunkle, 2004). The constraints on an individual are dynamic, interacting and fluctuating over time (e.g., with learning, age or development) (Davids et al., 2008). This interaction among constraints was highlighted in postural coordination tasks in which the task constraints (the amplitude of the target) interacted with the organismic constraints (the height of the center of gravity) (Bardy et al., 1999). In this study, the authors showed that when the center of gravity was lowered, subjects were in antiphase only for target amplitudes of 35 cm, whereas for a high center of gravity the antiphase mode appeared at 14 cm, and in normal conditions at 18 cm.

In fact, a coordination pattern emerges from the dynamic interaction of all three types of constraint, and behavioral variability allows for the continuous adaptation to changes in them. Coordination emerges from functional information-movement coupling, a concept which emphasizes that coordination is dependent on mutual interactions inherent to a practice setting and the individual's activity (Figure 5) (David et al., 2008; Davids, Glazier, Araújo, & Bartlett, 2003).

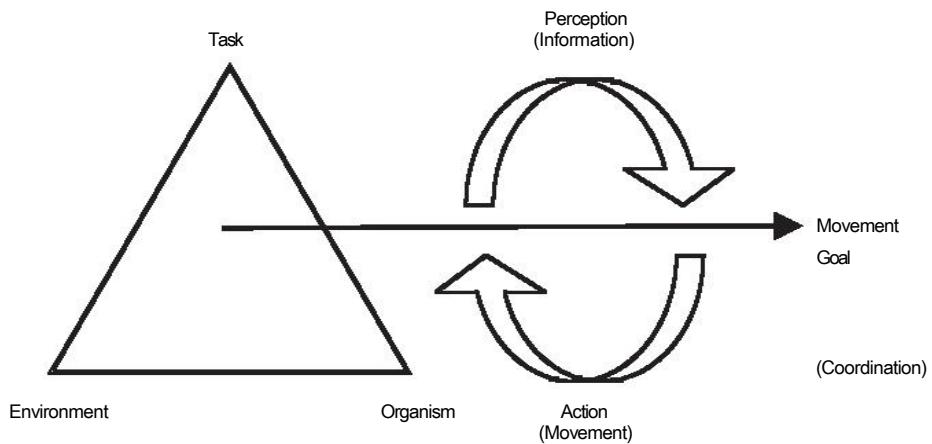


Figure 5. Representation of coordination emerging from the interaction of constraints through perception-action coupling (Davids et al., 2008).

Gibson (1979) postulated that movement generates information, which in turn supports other movements, leading to direct perception and the coupling between perception and action. Movements produce changes in energy flow, thereby providing specific information on the environmental properties that can be used by individuals as possibilities for action [i.e., affordances (Gibson, 1979)]. Affordances are the possibilities for action offered by interacting constraints, without these constraints necessarily being either inherent to an object or in the environment. They are specific to the individual in the sense that they are related to the individual's personal capacities (David et al; 2008; Fajen, Riley, & Turvey, 2009). For example, in a task of intercepting a football pass, the positions of teammates and opponents on the field, the player's skills, and the quality of the playing field all constrain the possibilities for action during the interception (Travassos et al., 2012). More precisely, in a perceptual-motor task, it is the interaction between intention, perception and action that constrains movement through the perception-action cycle (Seifert & Davids, 2012; Shaw, 2003).

This classification system resulted in the "constraints-led approach" (Davids et al., 2008) to studying coordination as emerging from the impact of interacting constraints on the system. This approach lies at the interface of theories of motor control, biomechanics, behavioral neuroscience and psychology (Beek, Peper, & Stegeman, 1995; Davids & Glazier, 2010; Glazier, Wheat, Pease, & Bartlett, 2006). For example, an important aspect of human biomechanics, within-subject and inter-subject variability, is likely to be overlooked in traditional biomechanical studies because of data filtering, smoothing and averaging, whereas such variability might be of paramount importance in studies of coordination that focus on organismic constraints (Glazier & Davids, 2009a, 2009b). Using this approach, it is possible to examine the effect of a specific constraint on the emergence of coordination while bearing in mind that changing one constraint will change the dynamic interaction of all constraints on the individual. For example, the predominant effect of many of the constraints on swimming coordination has been investigated [e.g., the effect of expertise (Leblanc et al., 2005; Seifert, Chollet, & Rouard, 2007; Seifert, Delignières, Boulesteix, & Chollet, 2007; Seifert, Leblanc, Chollet, & Delignières, 2010), gender (Seifert, Boulesteix, Carter, & Chollet, 2005; Seifert & Chollet, 2005), the increase in energy cost (Komar et al., 2011) and swimming specialty (Seifert, Komar et al., 2010)]. Taken together, these studies have shown that modifying one of the constraints acting on an individual was able to provoke a phase transition in motor

behavior (e.g., a shift from catch-up coordination to superposition when swimming speed increased [Chollet, Chalies, & Chatard, 2000]). This constraint thus acts as a control parameter that changes and destabilizes the initial coordination. The stability of a coordination pattern is thus relative, and a regime of multistability and phase transitions underlies the complex mechanisms of stability and loss of stability.

Between stability, flexibility and pluripotentiality: The functional role of variability

Although variability has traditionally been perceived as random noise to be minimized (K. M. Newell, Deutsch, Sosnoff, & Mayer-Kress, 2006), behavioral variability may play a functional role in motor control (Davids et al., 2006). This variability is observed between individuals and between the trials or cycles of the same individual, and it may concern a range of parameters (i.e., superficial, like the frequency or amplitude of movements, or profound, like coordination patterns). According to Newell and Corcos (1993, p. 1), "variability is inherent both within and between biological systems" and movement variability helps to stabilize performance. In this case, we refer to the functional role of variability, as it allows individuals to explore efficient solutions for a specific task and to continuously adapt to their own characteristics as well as to changes in the environment (Davids et al., 2004; Harbourne & Stergiou, 2009; Riley & Turvey, 2002; Seifert & Davids, 2012). More generally, variability is observed at many levels of analysis (from genes to motor behavior) and operates at different time scales (Harbourne & Stergiou, 2009). The origin of variability lies in the specific degenerative architecture of neurobiological systems. According to the concept of *degeneration*, the variability in neurobiological systems produces (i) the relative stability of motor functions undergoing external disturbances, (ii) behavioral flexibility in response to changes in the environment, and (iii) the appearance of new behaviors in order to increase task performance.

Neurobiological degeneracy: supporting stability, flexibility and pluripotentiality

In 1954, George Gamow introduced a new concept in genetic biology by defining the possible encoding of amino acids by more than a single nucleotide triplet as degenerative (Crick, 1955), thus explaining how 64 nucleotide triplets encode only

about 20 amino acids. The concept of degeneration captures not only the ability of the structurally different components of a neurobiological system to perform the same task under certain conditions, but also the ability of these components to assume distinctly different roles in other conditions (Edelman & Gally, 2001; Tononi, Sporns, & Edelman, 1999). What Gamow did not highlight is that this degenerative phenomenon has many levels of complexity. For example, the principle of degeneration in neurobiological systems is found in neuronal connections, synaptic plasticity, sensory modes, body movements, and even interpersonal interactions (Edelman & Gally, 2001; Mason, 2010). Kay (1988, p. 344) referred to coordination as "a temporary and flexible assembly of many micro-components in such a way that a single micro-component can participate in several different coordinating structures on different occasions," thereby taking into account the degenerative aspect of motor coordination. Degeneration in fact refers to two types of relationship: *many structures-one function* and *one structure-many functions* (Price & Friston, 2002). In neuromusculoskeletal organization, degeneration corresponds to the architecture of the joints involved in the performance of a function or task (Figure 6). In Figure 6, we can observe that the same function can be performed by two different architectures, each involving different joints (i.e., many structures-one function), as well as by several joints working together (i.e., one structure-many functions), all the while leaving some joints free for future involvement. Although this type of functional architecture has sometimes been considered as "harmful for human behavior" (Cohen, Hershberg, & Solomon, 2004, p. 995), it ensures the stability and flexibility of coordination, and in addition allows for a certain pluripotentiality (Mason, 2010).

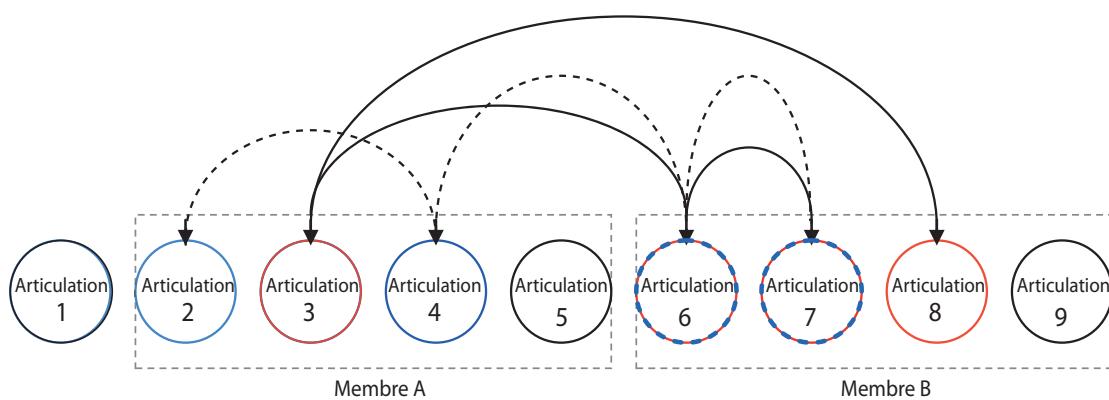


Figure 6. Schematic representation of degenerative organization: the same function is performed by organization A (dotted line) involving joints 2, 4, 6 and 7, or by organization B (solid line) involving joints 3, 6, 7 and 8. Joints 1, 5 and 9 are available if needed (adapted from Delignières, Marmelat, & Torre, 2011).

The first characteristic of a degenerative system is its ability to accomplish the same task in different ways. This feature has been highlighted in tasks of ski simulation (Hong & Newell, 2006a), pedaling (Chen, Liu, Mayer-Kress, & Newell, 2005), free-throws in basketball (Rein and al., 2010), and ball strikes in football (Chow et al., 2009). Hong & Newell (2006), for example, showed that their subjects were able to use different patterns of inter-segmental coordination in order to achieve the desired coupling between their center of mass and the ski platform. At the local level, the joint organization differed, although a similar functional outcome was observed at the global level. Kelso identified this as the "principle of functional equivalence" (Kelso, 2012, p. 907). Although they are often confused, degenerative and redundant systems are different in nature and the former is preferred for the description of neurobiological systems (Edelman & Gally, 2001; Price & Friston, 2002; Tononi et al., 1999). The notion of redundancy is best adapted to machines (Davids & Glazier, 2010; Latash, 2000, 2012) as it expresses the idea of the multiplication of system elements in order to ensure stability and functional equivalence. For example, all navigation systems in a plane are identically duplicated; thus, if one system fails, it can be replaced by the second version. A redundant system is isofunctional and isomorphic, while a degenerative system is isofunctional but not isomorphic (Mason, 2010). In other words, different structures or different assemblies of these structures in a degenerative system can lead to identical functions (Edelman & Gally, 2001).

The elements of a degenerative system therefore share the same function but do not share the same overall structure (Whitacre, 2010), which supports the observation of different coordination patterns used to perform the same task. The possibility of several ways to achieve the same end creates a potential for movement variability that protects the body against environmental disturbances. Along the same lines, Delignières et al. (2011) associated degeneration with long-term correlations. The authors showed that increasing the degenerative character of a system augmented the long-term correlations. These long-term correlations in fact only appeared when enough separate networks were involved in performance over time. Degenerative architecture thus appears necessary for the appearance of these correlations, which characterize the movements of complex systems that are both stable and adaptive. Thus, the functionality of a degenerative system is not easily destabilized because it is distributed across an entire structure of components that are different but self-

organized according to the situational constraints (Mason, 2010) to ensure system stability and robustness (Whitacre & Bender, 2010; Whitacre, 2010).

This non-isomorphism is the origin of the second major characteristic of degenerative neurobiological systems: the flexibility of coordination patterns. In different contexts, the same degenerative system has the potential to produce different functions, and thus it exhibits flexibility with regard to a new or changing environment. In the case of football, Chow et al. (2007) showed functional adaptation during a ball strike; that is, the intra-individual differences depending on the task at hand. Specifically, the players showed an adaptation of foot speed depending on the distance from the target. This type of functional intra-individual variability was also highlighted at the level of subject-environment coupling. Pinder et al. (2012) showed that in cricket, depending on the distance that the ball bounced before being hit, the batsmen were able to adapt their behavior in order to perform the task efficiently. In swimming, Seifert et al. (2004) showed that crawl swimmers adopted a specific mode of inter-arm coordination for slower paces ("catch-up" at 3000-m to 200-m paces), and used a different coordination mode for faster paces ("opposition" or "superposition" for 100-m to 50-m paces). Similar changes in inter-segmental coordination were observed in breaststroke and butterfly by studying the arm-leg relative phase (Seifert, Delignières, et al., 2007; Seifert, Leblanc, et al., 2010).

In all these cases, the same system components carry out different roles depending on the nature of the task and environmental constraints; that is, these components can organize differently. In a basketball shooting task, Rein et al. (2010) conducted a cluster analysis and showed that, depending on the shooting distance, the players moved from one cluster to another, thus adapting their movements to the task constraints. However, in this experiment, the subjects specifically adopted a new pattern when shooting 4 m from the basket. This new pattern appeared to be less stable than the initial pattern, so much so that the authors suggested that this drop in stability was due to the recruitment of additional degrees of freedom. In other words, adaptation to constraints sometimes requires going beyond the initial repertory and completely changing our behavior (e.g., opening a door with your foot when both arms are full). This introduces the third and perhaps the most important characteristic of degenerative systems: their pluripotentiality (Mason, 2010). Indeed, degenerative systems exhibit a partial overlap in their component functions (Delignières et al., 2011), and the elements of a neurobiological system can sometimes be mobilized for the same function and sometimes for different functions. In addition, for every task,

the level of mobilization of the various system components is heterogeneous. In fact, every system element can be highly mobilized for one task, and very little for another. Due to the partial overlap of component functions, there is a different potential mobilization for the elements in a degenerative system. Degeneration thereby creates a surplus of structure for future exaptations (Mason, 2010; Whitacre, 2010). In other words, during the performance of a motor task, some limbs or joints may be only slightly mobilized, but they may potentially be far more mobilized in the future. Thus, this pluripotentiality is expressed when a neurobiological system is neither in an organized and stable regime nor in a completely disorganized system, but rather in a *metastable* regime (Kelso, 2012).

Beyond stability: metastability

In the theory of dynamical systems, metastability is a regime similar to a saddle-node bifurcation, in which no pattern of stable coordination actually exists but the initial attraction to what the attractors were still persists (Kelso, 2008). More specifically, metastability comes from the Latin words *meta* (beyond) and *stabilis* (stability) and thus refers to a certain type of instability that lies beyond stability. This condition is therefore not really a stable relationship, without referring to a relationship that is completely unstable. In a metastable region, "there is attractivity but, strictly speaking, no attractor" (Kelso & Engström, 2006, p. 172). Thus, metastability can be defined as the simultaneous production of two *opposing tendencies*: the tendency of several components to couple (integrative tendency) and the tendency of these components to each express their individual behavior (segregated tendency) (Kello , Anderson, Holden, & Van Orden, 2008; Kelso et al.; 1991; Kelso & Engström, 2006; Kelso, 1995, 2012). Metastability thus formalizes the balance between the phases of order and disorder in a complex system close to the critical state (Kello, Beltz, Holden, & Van Orden, 2007).

Recent investigations at the scale of brain organization suggest that metastability has a central role in describing the interactions between neurons (Fingelkurts & Fingelkurts, 2004; Tognoli & Kelso, 2009). Studies of the connectivity between brain areas have shown that a metastable regime is more favorable to cognition, and more specifically that complexity peaks when integration and segregation are balanced (Sporns, Tononi, & Edelman, 2000; Tononi, Edelman, &

Sporns, 1998), with this high level of complexity being the basis for new interactions between neurons. Friston (1997) studied the spectral density of neuronal connections (in groups of 6, 8 and 16 neuronal units) and demonstrated the expression of several successive coordination patterns (i.e., dense connectivity between neurons), therefore described as transient. These authors reported the recurring creation-destruction of coordination that creates the impression of continuous instability with the attractor is constantly changing. However, for very short periods of observation, some stability is observed, supporting the idea that a metastable state does not reflect a complete lack of coordination. This phenomenon is related to the phenomenon of *intermittency*, which defines a system equilibrium that is close to a critical state, from which it can shift spontaneously from a coordinated to a disordered state (Kelso, 1995).

At the scale of motor coordination, Von Holst (1973) had early on referred to a *magnet effect* (i.e., integration tendency) and a *maintenance tendency* (i.e., segregation tendency) as essential to the complete description of coordination in all its forms. The metastable regime of coordination shows that this is true: the two tendencies are actually the result of the interrelationship between the non-linear coupling of elements and their intrinsic dynamics. In the metastable regime, the usual measures of coordination dynamics no longer appear to be valid. In this case, the study of coordination stability, the loss of stability, critical fluctuations, and relaxation time (see Chapter 1) no longer apply, mainly because this regime does not actually define a coordination state, but rather the "traces of coordination" (Kelso, 2008, p. 190).

To summarize, Figure 7 shows the evolution of an order parameter. In the case of a multistable system (Figure 7a), we note that, regardless of the initial value of the relative phase, all trajectories converge over time toward an attractor at $\phi \approx 0$ rad. modulo 2π or a second attractor $\phi \approx \pi$ rad. modulo 2π (the regime is bistable here). Unlike in a monostable regime (Figure 7b), all trajectories converge toward a single attractor equal to $\phi \approx 0$ rad. modulo 2π , and this no matter what the initial state of the coordination at $t = 0$. Figure 7d shows no coupling between the oscillators, a situation in which no convergence toward one or more stable states is observed. Concerning the metastable regime (Figure 7c), the trajectories represent tendencies toward stable coupling at $\phi \approx 0$ rad. modulus 2π (7c 1), but are interspersed by tendencies with no coupling (7c 2). In this region, the system behavior is neither completely ordered (i.e., synchronized) nor completely disordered (i.e.,

asynchronized), but rather a mixture of both (Kelso, Dumas, & Tognoli, 2013; Tononi, Sporns, & Edelman, 1994).

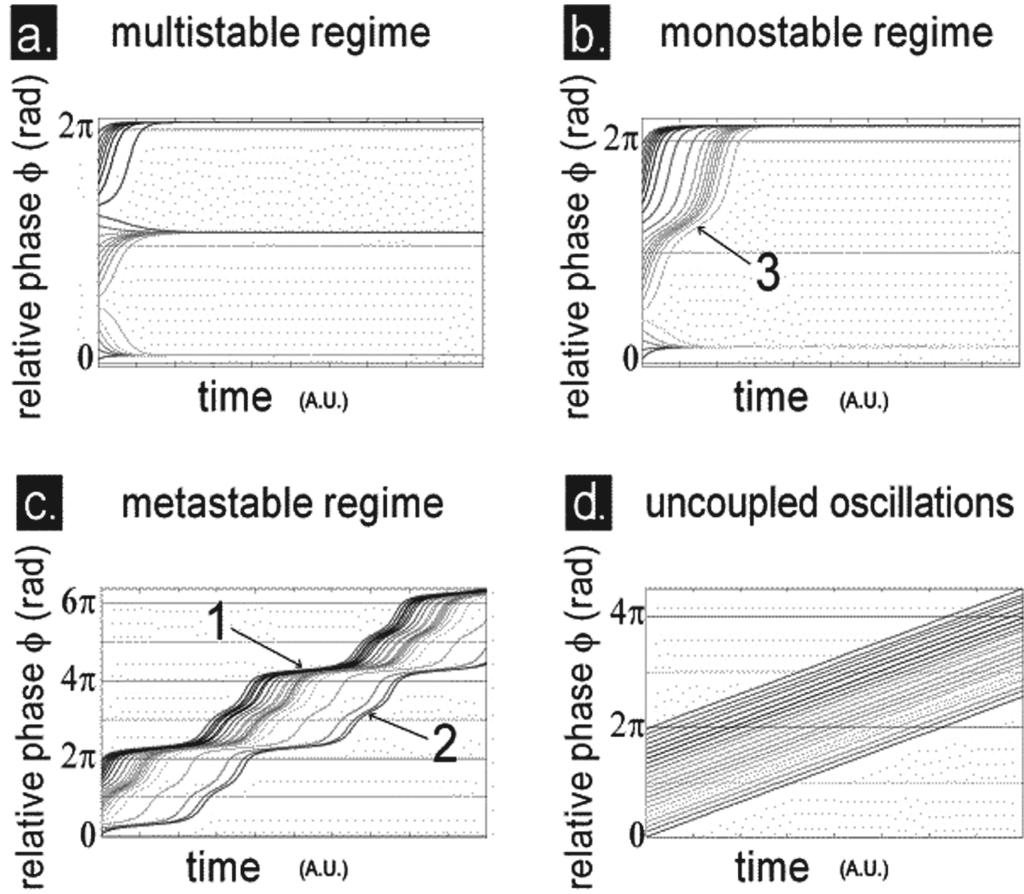


Figure 7. Evolution of the relative phase in different coordination regimes: a. multistability, b. monostability, c. metastability, and d. absence of coupling (Kelso, 2008, p. 191)

More specifically, metastability results from *symmetry-breaking* in a system of coupled oscillators (Kelso, 2008). The symmetry between the two oscillators is defined as "a transformation that leaves the system identical to what it was before" (Kelso, 1995, p. 54). For example, if we conduct Kelso's experiment on bimanual coordination (Kelso, Holt, Rubin, & Kugler, 1981) in front of a mirror, the phase relation between the two fingers remains the same, and there is thus spatial symmetry. Similarly, if we advance one oscillator by one period, the phase relation between the two fingers is also the same, and there is thus temporal symmetry. In other words, as long as the phase relation between two oscillators does not change when the oscillators are reversed, the time-space symmetry between the two oscillators is respected. Kelso and Jeka (1992) express this idea simply by the fact that in this situation of symmetry, the

movement corresponding to a relative phase ϕ is equal to the movement corresponding to its opposite relative phase $-\phi$. In a situation of symmetry between two oscillators, the only relations between the two fingers are in-phase and antiphase (modulo 2π). Indeed, if there is a phase shift, even slight, between the two oscillators, relative phase ϕ is not equivalent to relative phase $-\phi$. Symmetry is broken in all other cases. An experiment to study this asymmetry focused on the temporal symmetry between the hand and a metronome and showed how the symmetry between the two elements evolved according to the oscillation frequency (Kelso, DelColle, & Schöner, 1990). This symmetry-breaking in relative coordination is only a reflection of the individual behavior of each oscillator in the system. In any case, the main point is that any situation that is able to generate spatial and temporal differences between system elements is potentially a source of asymmetry (by accentuating or reducing it). For example, using the MAC, Jeka et al. (1995) showed that by increasing the mass of a limb it was possible to create asymmetry and thus completely change the attractor landscape. Similarly, environmental demands, intention, or learning can alter the symmetry of coordination dynamics, thus promoting or reducing the appearance of a metastable system (Kelso & Engström, 2006; Kelso, 2008, 2012; Vilar et al., 2012).

In fact, it is the subtle interplay between the strength of the coupling between oscillators ($k = b/a$) and the term of the symmetry-breaking ($\delta\omega$) that gives rise to metastability (Kelso, 2002). Increasing or decreasing the asymmetry between oscillators, as well as changing the strength of the coupling between the oscillators, can promote or discourage the appearance of metastability. To formalize the relationships among metastability, monostability and multistability, Figure 8 shows the range of possible regimes depending on the strength of coupling (b/a) and the symmetry-breaking between the oscillators ($\delta\omega$). Thus, the weaker the coupling between oscillators is, the higher the probability of seeing a metastable regime. Conversely, this probability becomes lower as the coupling becomes stronger. Any practice that enhances the coupling between oscillators therefore makes it more difficult for a future metastable regime to be reached. Similarly, the weaker the asymmetry between the oscillators, the more difficult it will be, if not impossible, to achieve the metastable regime, and vice versa.

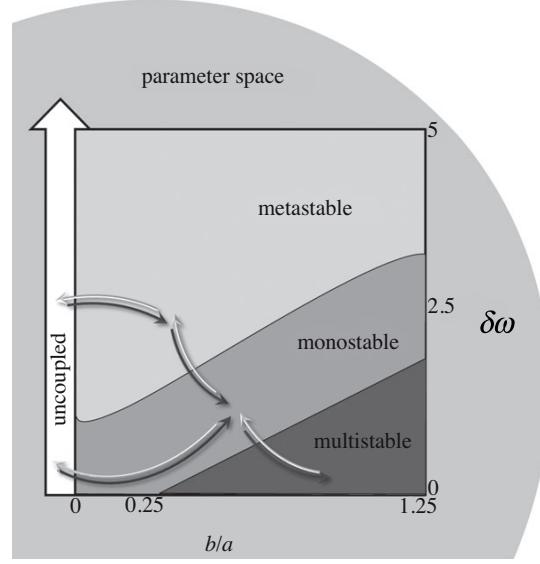


Figure 8. Representation of the parameter space showing the coordination regimes that are possible, depending on the coupling strength and the oscillator symmetries (modified from Kelso, 2012).

Recently, the characteristics of the metastable regime were investigated at the level of subject-environment coupling. In a task of hitting the cricket ball after a rebound, Pinder et al. (2012) reported a rebound zone for which the batsmen did not show stable behavior while hitting the ball. When the ball rebounded 7.5 m from the batsmen, they sometimes moved forward and sometimes backward in order to strike. The movement, the contact time and the direction of the strike showed great variability in this zone (Figures 9 and 10.3). In contrast, these parameters showed high stability when the ball bounced in zones closer to (Figure 9, 10.1 and 10.2) or more distant (Figure 9 and 10.4) from the batsmen.

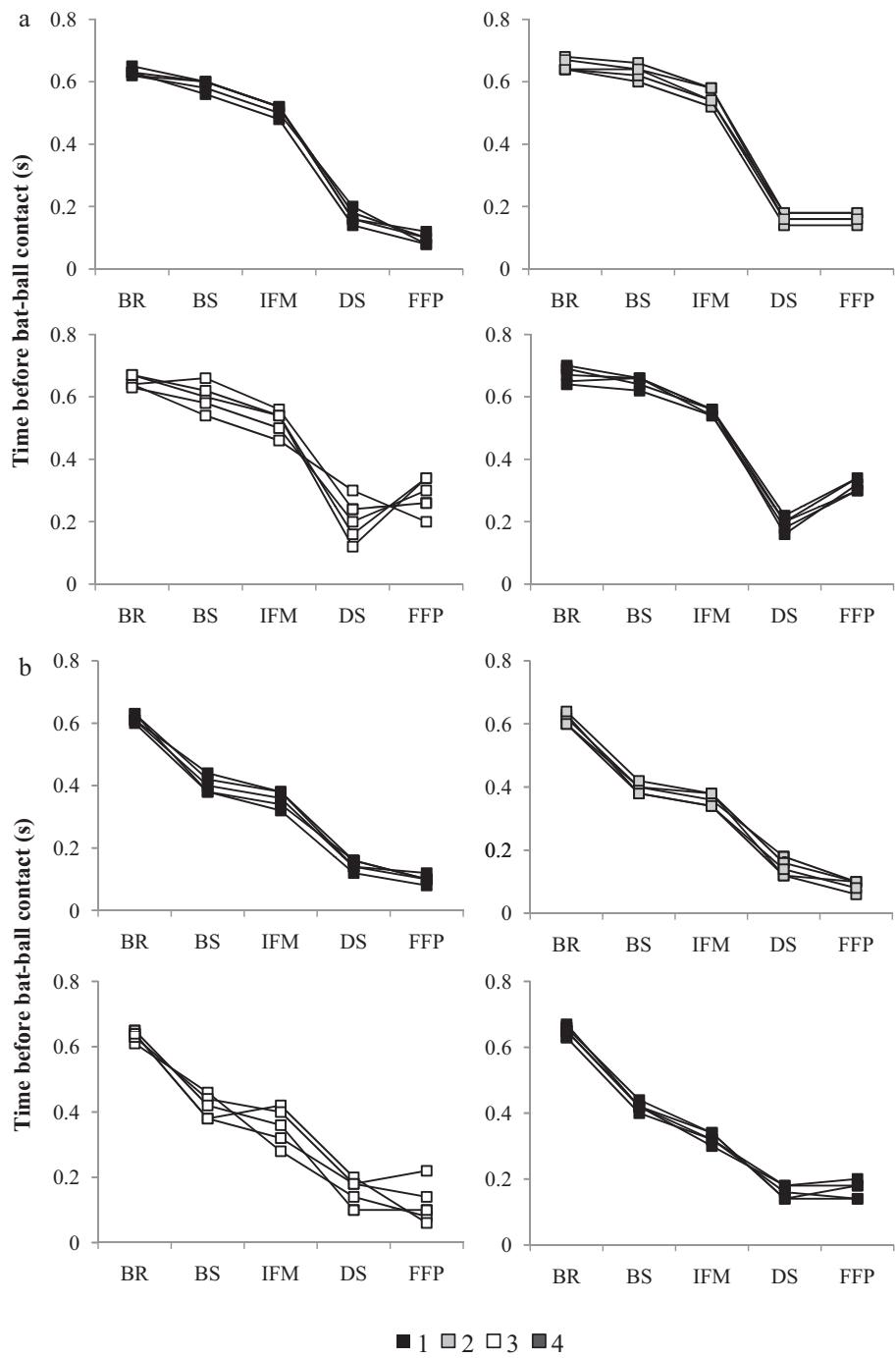


Figure 9. Representation of the variability in the ball-bat contact time, depending on the rebound zone of the ball (white squares represent zone 3) (Pinder et al., 2012).

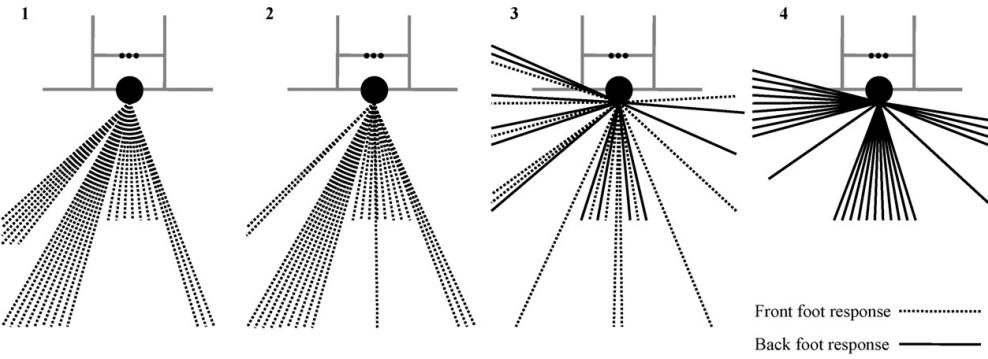


Figure 10. Representation of the types of behavior (dotted lines for “feet-forward” responses and solid lines for “feet-backward” responses) and the directions of the ball rebound (Pinder et al., 2012).

Hristovsky et al. (2006) worked along similar lines with novice boxers and showed how the ratio of the distance between the punching bag and the boxer and the boxer’s arm length could be used to define zones of stable behavior and unstable behavior (when the boxer-bag distance is about 0.6 times the arm length). Indeed, at a critical distance of 0.6 times the arm length, boxers showed a range of behaviors, whereas outside this zone, their behavior was very stable. In this metastable regime, one or more patterns appeared slightly stable or slightly unstable, and the shift from one pattern to another occurred under the influence of the system constraints (Hristovski et al., 2006). These results are of paramount importance and they suggest that in the metastable regime, people can assemble and explore new functional solutions to deal with task constraints (Hristovski et al., 2006; Pinder et al., 2012.). The functionality of metastability is supported by the observation that in this metastable region, the cricket batsmen always appeared to be as efficient as in stable regions (Pinder et al., 2012). The authors thus suggested that in this region, people have easier access to the various alternative options to perform a task. By manipulating the control parameters or the degree of asymmetry between oscillators, it may thus be possible to make new behaviors emerge (Araújo et al., 2006; Chow et al., 2011; Hristovski, Davids, & Araújo, 2009; Kelso & Engström, 2006)—and therefore to promote learning? This regime may be a particular state [the “transitional stationary” state of a complex system (Kelso, 2008, 2012)] and therefore is more than just a phase transition between two stable states (Kelso, 1995). In fact, in the metastable regime, coordination is really only a tendency that needs to be expressed: it is conceivable that metastability is the ideal regime for innovation and learning

Chapter 2: The dynamical approach to motor learning

Modification in the intrinsic dynamics and exploration of the work space

Cooperation, competition and learning stages

According to dynamical systems theory (Kelso, 1995), motor learning is a transition from one stable state to another (Schöner, Zanone, & Kelso, 1992; Zanone & Kelso, 1992). Learning is a modification in the initial attractor landscape or *intrinsic dynamics* (Zanone & Kelso, 1992). This modification can occur in two ways: (i) the appearance of a new attractor or (ii) the stabilization of an attractor already present. From this perspective, the stability of one or more coordination patterns defines the property of learning (Kostrubiec, Tallet, & Zanone, 2006; Tallet, Kostrubiec, & Zanone, 2008). Learning thus implies a modification in the initial stability of the individual's intrinsic dynamics, which may in turn lead to the creation of a new coordination pattern, but this is not necessarily so. The acquisition of motor skills also requires learning to interact effectively with the environment, detect relevant information, and respond appropriately. Learning thus also resides in the adaptability of the coordination dynamics that we stabilize (i.e., in the stability-flexibility relationship) (Button, Chow, & Rein, 2008).

In fact, the entire set of intrinsic dynamics seems to be modified with learning, rather than a single attractor disappearing so that another can appear (Kelso, 1995; Schöner et al., 1992; Walter, 1998; Zanone & Kelso, 1992, 1997). Zanone & Kelso (1992) showed that learning a 90° phase shift in bimanual coordination brings about the complete reorganization of the coordination dynamics. In addition to stabilizing a new attractor at a relative phase of 90°, such learning also brings about a modification in the stability (stabilization or destabilization) of other initially stable patterns (0° and 180°) (Zanone & Kelso, 1992). In a nearly identical experiment, Zanone and Kelso (1997) showed that learning one pattern led to the stabilization of the symmetrical pattern [i.e., the *principle of symmetry conservation* (Kelso & Jeka, 1992; Zanone & Kostrubiec, 2004)]; that is, when a person learns a pattern at 90°, the pattern at 270° also stabilizes without having to be repeated, and thus the whole dynamic of coordination is modified. Evaluating the intrinsic dynamics takes place through a *scanning probe or scanning procedure*, which means incrementally

assessing the stability of all possible coordinations from 0° to 180° or 360° (e.g., Faugloire, Bardy, Merhi, & Stoffregen, 2005; Faugloire, Bardy, & Stoffregen, 2009; Zanone & Kelso, 1992, 1997). By identifying the intrinsic dynamics, the system states that are preferentially adopted can be determined, as can those that are generally difficult to access, such as learning. When an individual is confronted with a new task, the coordination to be learned may be close to the individual's intrinsic dynamics. In this situation of *cooperation*, learning consists of optimizing an existing coordination. Conversely, when the coordination to be learned is far from the intrinsic dynamics, the situation is called *competition* and learning involves setting up a new zone of stability (Zanone & Kelso, 1992).

Competition-Cooperation. From this perspective, learning is the product of a relative competition-cooperation between the learner's intrinsic dynamics and the extrinsic requirements (Schöner & Kelso, 1988b; Zanone & Kelso, 1992, 1997). These extrinsic influences, as opposed to the intrinsic dynamics, include memory, intentions, and the environment (Schöner & Kelso, 1988c) and, when compared with the constraints-led approach, they are found to correspond to the task and environmental constraints acting on the individual (e.g., the regulatory imposition of a specific pattern). More specifically, a competitive situation causes a qualitative reorganization of the learner's intrinsic dynamics; that is, in such a situation, the nature or number of attractors in the individual's intrinsic dynamics differs after learning (Schöner et al., 1992). Conversely, a cooperative situation does not generate a qualitative reorganization of the dynamics in the sense that the nature and the total number of attractors in the learner's intrinsic dynamics does not change during learning. This distinction between competition and cooperation was demonstrated in experiments on bimanual coordination, in which initially bistable individuals became tri-stable with the stabilization of a third attractor (competitive situation, Figures 11.a and 11.c). In contrast, initially tri-stable individuals remained tri-stable after learning but modified their intrinsic dynamics through a shift in the coordination patterns. For example, coordination initially stabilized at 90° shifted during learning to 135° (cooperation position, Figures 11.b and 11.d) (Zanone & Kelso, 1992).

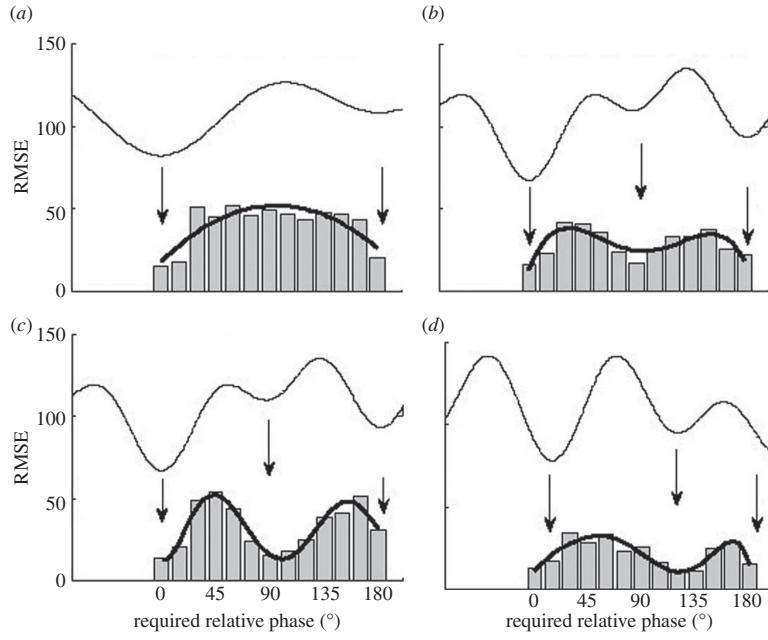


Figure 11. Representation of the attractors (basins in solid lines) before learning (top) and after learning (bottom). The bars represent the mean error of the relative phase (abscissa). The right column represents a cooperative situation where the number of attractors does not change with learning and the right column represents a competitive situation where a new attractor appears after learning (Kelso, 2012).

The distance between the intrinsic dynamics and the pattern to be learned defines the intensity of competition (Schöner, 1989), and the competition-cooperation distinction takes a form more similar to a continuum than a dichotomy. For example, in bimanual coordination, Kostrubiec & Zanone (2002) defined the distance between the initial stable pattern (0° or 180°) and the 90° pattern by a differential of 90° . Similarly, the distance between the intrinsic dynamics (0° or 180°) and a 135° pattern to be learned is 45° . Competition is thus greater when learning a pattern at 90° than at 135° .

Schöner (1989) suggested that in a situation of cooperation, competition is low and the system can eliminate it by shifting from an initially stable state to the state to be learned. Conversely, when competition is higher, shifting to the pattern to be learned is impossible, the competition continues and, to escape the pressure of competition, the system must bifurcate, thereby creating a new stable state. Whereas a learning situation with low competition leads to a quantitative fit, with parametric changes producing coordination (Zanone & Kelso, 2002; Zanone & Kelso, 1997), a learning situation with high competition results in a bifurcation, with a qualitative change in the intrinsic dynamics. The nature of the transition (i.e., abrupt or gradual)

during learning depends on the intensity of the competition between the intrinsic dynamics and the pattern to be learned (Kostrubiec, Zanone, Fuchs, & Kelso, 2012). Interestingly, a situation of cooperation could lead to a relatively rapid increase in the accuracy of the pattern to be performed, followed by slower stabilization (i.e., decreased variability), whereas a competitive situation results in a simultaneous increase in the accuracy and stability of the pattern that is being learned (Zanone & Kostrubiec, 2004). In addition, the time required for learning (i.e., to achieve high accuracy and low variability) is longer in a cooperative situation than a competitive situation (Zanone & Kostrubiec, 2004).

The question raised by the notion of high or low competition is whether learning actually occurs in a situation of cooperation. The fact that the learner is already able to produce coordination close of that being learned suggests that this is more a case of optimizing a coordination that already exists. However, it seems that the cooperative situation corresponds to real learning, but mainly in the final stages of acquisition where the learner's objective is to perfect his or her coordination by making it more flexible, stable, and efficient. In contrast, the situation of competition suggests the early stages of learning, where the learner seeks to create a new attractor through a transition from novice behavior to expert behavior.

Stages of learning. The definition of learning stages has resulted in many learning models (e.g., Adams, 1971; Fitts, 1964; Mark L Latash, 2010). Newell's model is widely accepted within the ecological dynamics framework (1985). This model is based on Bernstein's principle of managing degrees of freedom (1967), but focuses particularly on the stabilization and changes in coordination that occur with learning. According to Newell (1985), the first stage, *coordination*, refers to the assembly of body segments so that they can respond effectively to a given task. In other words, the learner puts together the movements of the key segments involved in the action (Davids et al., 2008), such as the arm, forearm, thigh and leg in breaststroke. Coordinating patterns are formed at this stage to allow the learner to perform the task, even though the coordination is not very flexible or adaptable. There may be a temporary freezing of the degrees of freedom in the body at this stage, as well, in order to better control the sheer abundance of them (KM Newell, 1996). Bernstein (1967) first advanced this idea and likened it to locking certain joints in order not to have to control them. By doing so, novices manage to control a movement because they have only a small number of elements to control (i.e., only those joints not locked).

During the second stage of *control*, a progressive relaxation or unfreezing of rigid joints takes place and more joints are then involved in the task. This gradual process is made possible by the stabilization of the initially assembled coordination patterns. In fact, it appears that the relatively rigid coordination that was first assembled is gradually freed for reorganization through different configurations, without this necessarily implying the freeing of mechanical degrees of freedom (Hong & Newell, 2006a). The principle of freezing-unfreezing the degrees of freedom while learning seems to be highly dependent on task constraints (Newell & Vaillancourt, 2001). It was not observed in a pedalling task (Hong & Newell, 2006a) and only partially in a football task (Chow, Davids, & Button, 2007), but was strongly operative in various experiments with ski simulators (Vereijken Van Emmerik, Bongaardt, Beek, & Newell, 1997; Vereijken et al., 1992) or during volleyball serves (Temprado et al., 1997). In these experiments, novice subjects showed a small range of motion in the first sessions (i.e., revealed by small standard deviations in joint amplitudes) but, after several practice sessions, these joints were more actively involved in the movement (i.e., two- or threefold increase in the standard deviations). The learner's goal at this stage is to put into place more precise couplings between body segments and higher-order constraints like speed or acceleration (Williams, Davids, & Williams, 1999), thereby arriving at a better balance between coordination and task constraints (Newell & Vaillancourt, 2001). Indeed, from this stage, a change in the speed of foot-ball contact is seen in football, and the greater the distance of the target, the higher the foot speed becomes (Chow, Davids, & Button, 2007). This stage corresponds to the development of the degenerative aspect of the neuromusculoskeletal system because of the increasing number of degrees of freedom, or at least their reorganization, which makes coordination both more stable and more flexible. Among footballers, Chow et al. (2008) showed that the control stage was characterized by a decrease in the variability of coordination and thus an increase in its stability.

The third and final stage, *skilled*, corresponds to an optimization of the coordination pattern that the learner has made more flexible and adequate for the current constraints. This stage results in the optimal use of system reactive forces like gravity or buoyancy. Newell (1985) used the term "optimal" to refer to the energy efficiency that is observed during this stage. Once an individual reaches this final stage of learning, energy and/or mechanical efficiency is a major feature of the behavior (Sparrow & Newell, 1998). At this stage, the passive, inertial and

mechanical properties of body segments are used to the maximum to make movement economical and fluid (Davids et al., 2008). For example, the optimal use of gravity on the parallel bars was demonstrated by Delignières et al. (1998), who reported that expert gymnasts exhibited very specific coordination during the swing cycle (i.e., frequency ratio 2: 1 and a phase shift of 90°). The results revealed that with this specific coordination, experts were able to modulate the moment of inertia around the rotational axis, thereby exploiting gravity in the downturns and reducing its effect during the upswings. On a ski simulator, experts adopted behavior that took full advantage of the elastic returns of the device (Nourrit et al., 2003).

Based on Brainerd's idea (Brainerd, 1978), the assumption is that the transition from one stage to another occurs through collective qualitative changes arising from multiple factors, rather than a change in a single dimension of behavior (e.g., stabilization of coordination). The observation of several stages suggests that consecutive stages may overlap, rather than showing true and precise distinctions (Chow, Davids, Button, & Koh, 2008; Ko, Challis, & Newell, 2003; Peh, Chow, & Davids, 2011) and that the control stage can be achieved in some dimensions, but not in others. Chow et al. (2008) suggested that two stages are usually negotiated at the same time, as when the learner navigates between coordination and control, for example. Defining a learning stage therefore requires assessing changes on several dimensions; for example, in terms of the stability of the coordination or performance, or the flexibility of the coordination in the face of task constraints (Chen et al., 2005; Newell & Liu, 2012).

This model of learning stages is useful to distinguish the different levels of learners, such as *complete* novices who are discovering the task for the first time and are at the coordination stage, as opposed to "beginners" who know a minimum about the task and are between the coordination and control stages, or the "advanced learners" who have reached the stage of control (Peh et al., 2011). For example, an individual who enters the water for the first time is a real novice in swimming, whereas an individual who knows a minimum about how to move about in the water is a beginner already between the coordination and control stages (i.e., using a relatively stable coordination pattern, even though it is not adaptable, flexible or efficient). In contrast, an expert swimmer who has reached the skilled stage has stabilized an efficient coordination pattern and is able to adapt to the task constraints [e.g., swimming speed (Seifert, Leblanc et al., 2010)]. The learner's initial movement repertory, the intrinsic dynamics, can thus influence the nature of learning. More

specifically, individuals who are already at the control stage are only working to optimize their coordination (e.g., make it more stable, more flexible, and more efficient), whereas individuals at the coordination stage are trying to stabilize a new pattern, which ideally will involve the active exploration of their possibilities (Newell, 1991).

Towards exploratory learning

The idea of learning by active exploration of the workspace was initially proposed by Gel'fand and Tsetlin (1962). Motor learning occurs through motor exploration; that is, by the reproduction of (slightly) different movements or the use of a different neuromusculoskeletal organization (Goldfield, Kay, & Warren, 1993; van der Kamp & Savelsbergh, 1994). Gel'fand and Tsetlin (1962) described three types of exploration strategy during learning. The first is a *blind* strategy, where all points of the workspace will be explored in a specific or random order. The result of this exploratory method is not useful for future exploration. The second strategy is *local* and corresponds to a continuous search; moreover, the exploration at time t is dependent on the result of the previous exploration at time $t-1$. The past has a certain effect in this method that leads to the progressive discovery of expert behavior. The third strategy is *non-local* and it corresponds to a non-continuous search. This means that a temporary anchoring point is made at random within the workspace and exploration then continues around this point until another anchor is made and explored. Based on the work of Gel'fand and Tsetlin (1962), Newell et al. (Newell, Kugler, Van Emmerik, & McDonald, 1989) proposed three motor exploration strategies useful for developing a meaningful relationship between perception and action for a specific task. The authors described a blind method, a local method and a hybrid method (i.e., non-local) (Figure 12).

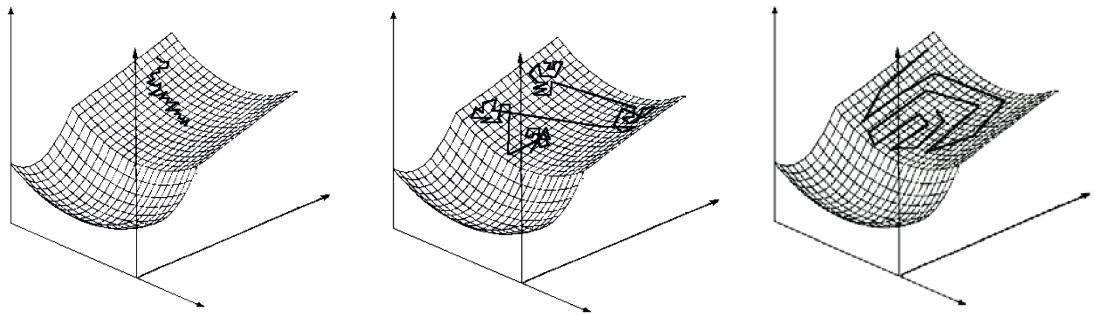


Figure 12. Exploration strategies: blind (right), local (left), hybrid or non-local (center) (Teulier, 2004).

Learners explore all the possibilities available to them at any given time, which is characterized as the *perceptual-motor workspace* (Newell et al., 1989; Newell, McDonald, & Kugler, 1991; Thelen, 1995). This *perceptual-motor workspace* is defined as the dynamic landscape from which coordination emerges based on the intrinsic dynamics and the constraints at that time (Thelen, 1995). It is the interface between perception and action and is delimited by all the interactions between the constraints on the system (Shaw & Alley, 1985). It is defined, for example, by the genetic code, developmental level, past experiences, social influences, etc., and is thus continuously shaped by perceptions, intentions, surrounding information, and physical constraints (Thelen & Smith, 1994). Navigating through the perceptual-motor workspace allows the subject to repeat the exploration process while being somewhat limited by the constraints, which reduces the set of possibles (Newell, 1991). During these repetitions, the learner's intrinsic dynamics will be changed through the stabilization of the new areas explored. Exploration plays an important role in enabling the learner to discover the optimal coordination pattern or patterns for a task, as well as the parameters that make for a flexible and efficient pattern. The workspace evolves qualitatively with ongoing practice because even the temporary stabilization of new explored coordination patterns allows further exploration to continue (Sporns & Edelman, 1993; van der Kamp & Savelsbergh, 1994). In these early stages, the goal of learning is to find the optimal workspace region, which corresponds to the coordination pattern that best satisfies the task, environmental and organismic constraints. Learning is seeking, exploring, discovering, assembling and stabilizing functional patterns (Newell, 1986, Williams et al., 1999). In relation to this exploration, variability during learning seems particularly interesting (Turvey & Fitzpatrick, 1993; van der Kamp & Savelsbergh, 1994).

Functional aspect of variability. As highlighted by Kelso and Engström (2006), variability in learning can take different forms. For example, a blind strategy may generate more alternation of several distinct behaviors because the explored space was randomly chosen up to the stabilization of a specific pattern. In contrast, a local strategy instead leads to a gradual transition because the exploration was made step by step on the basis of earlier explorations. A non-local strategy may lead to one or several transitions between patterns, interspersed with some variability around these anchors.

In a pedaling task, Chen et al. (Chen et al., 2005) used the Cauchy measure to quantify the variability in the degrees of freedom from one cycle to another (called relative variability) and showed that learning does not necessarily result in a simple linear decrease in variability⁴. Although all the subjects showed high variability on the first day of practice, and a certain convergence of behavior toward learning behavior at the end of practice, they found that the paths leading to the final stable behavior differed. The results revealed several profiles regarding the dynamics of relative variability. It thus appears that learning is not restricted to a reduction in the number of errors, trial after trial, culminating in the stabilization of the behavior to be learned. The degree of variability from one cycle to another, or from one trial to another, may evolve non-linearly over the course of practice. For example, the first profile showed an overall decrease in the relative variability with practice, but this was interspersed with several trials where exploration was very high (Figure 13.I). In other words, the overall exploration decreased with practice, even though periods of high exploration (i.e., as much as during the first sessions) persisted until late in the practice. This type of profile may reflect a *non-local* exploration strategy with several substantial behavioral changes followed by periods of smaller variation. Another profile showed the same overall decrease in relative variability interspersed with exploration peaks, but these peaks gradually decreased with practice (Figure 13.L). In this case, the amount of exploration decreased gradually over the course of learning, as if the learner was gradually drawing closer to the behavior to achieve. This type of profile seems to reflect a more *local* strategy, where exploration is based on previous explorations and a functional pattern is progressively achieved.

⁴ Conversely to computational approach that consider the decrease of the magnitude of motor variability as a paramount aspect during learning (e.g. Schmidt, 1985).

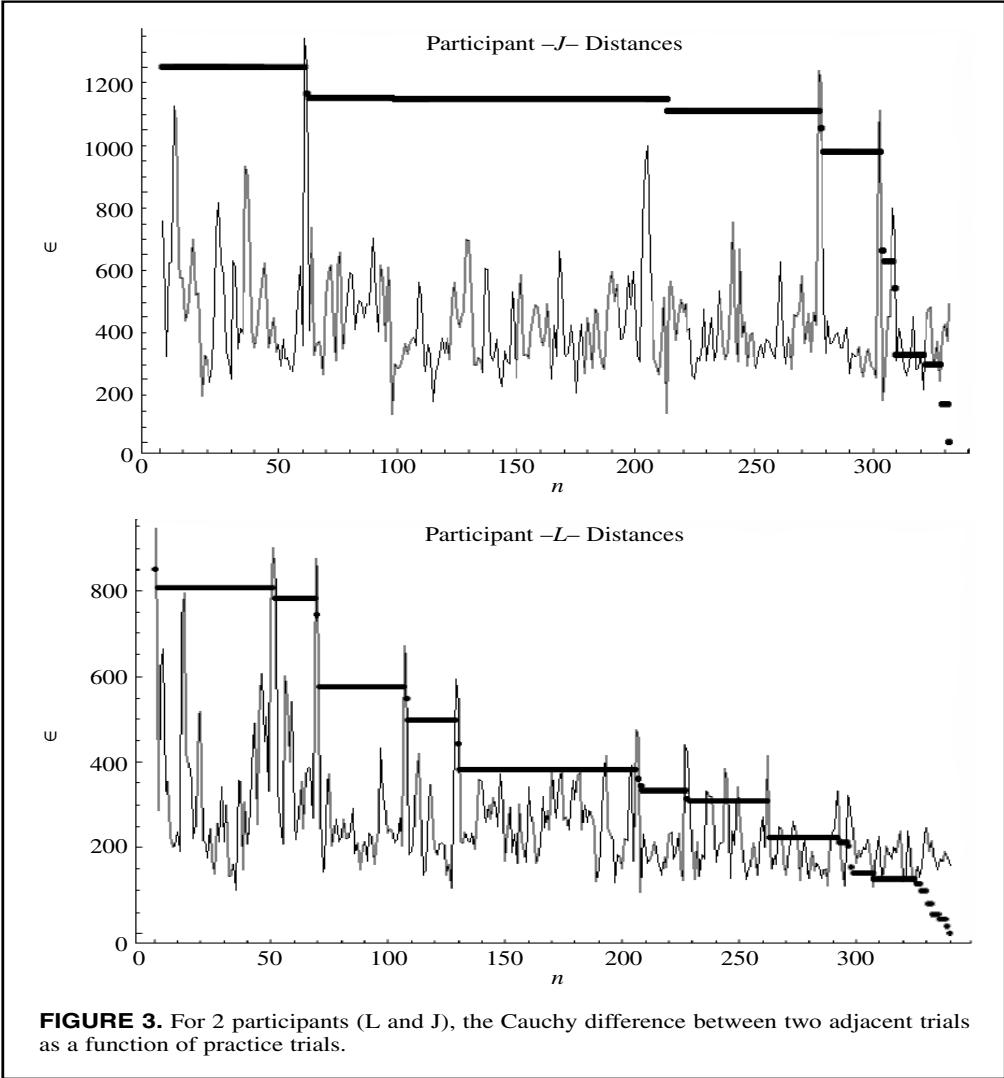


Figure 13. Time series of the cycle to cycle variability over 350 cycles. The thick dotted line represents the maximal variability (maximal amplitude) that persists between point n and the end of the series (Chen et al., 2005).

Whatever the strategy, it appears that implementing a process to manage the degrees of freedom in an activity involving many degrees of freedom requires, at least at times, periods of high instability (i.e., considered as periods of exploration). Chow et al. (Chow, Davids, Button, & Rein, 2008) showed that the acquisition of new coordination was preceded by a period of high increase in the variability of behavior. This phenomenon of increased variability may be related to the increase in critical fluctuations observed before a bifurcation (e.g., Schöner et al., 1986, Chapter 1, page 18). The process of acquiring new coordination seems to benefit from this variability, which suggests that the learning process is more complex than Bernstein thought (i.e., as the gradual freeing and control of degrees of freedom) (Hong &

Newell, 2006b; Newell & Vaillancourt, 2001) (even if precision is needed on the nature of the degrees of freedom, i.e., biomechanical or dynamic, that Bernstein refers in his book⁵. For example, in activities like playing the violin, it turns out that beginners exhibit a great involvement of the degrees of freedom. In contrast, freezing the elbow and shoulder is a sign of expertise through the stabilization of specific coordination (Konczak, Vander Velden, & Jaeger, 2009). Nevertheless, at the end of learning experts show greater freeing of the wrist compared with beginners. It thus seems that there is a distinction between the proximal and distal levels in the release of degrees of freedom and through this possibly some redistribution in the freezing/unfreezing of these degrees of freedom during learning. Studying the temporal dynamics of learning is one way to investigate the variability in the degrees of freedom; that is, to examine how and on what basis new coordination is manifested. Exploration may operate more or less abruptly and over longer or shorter periods through the back-and-forth between novice behavior and the exploration of possibilities, up to the point where a new pattern of coordination is stabilized (Teulier & Delignières, 2007).

Temporal dynamics of performance. Based on the first steps of Snoddy (1926) and Crossman (1959) Newell and Rosenbloom (1981) sought to describe the dynamics of learning by modeling the evolution of performance over time according to a power law, which they assumed was generalizable to learning. Since then, this linear perspective on learning dynamics has been widely criticized and is thought to be the result of methodological artifacts (i.e., short duration of experiments, low number of degrees of freedom involved in tasks, or loss of information through averaging (Newell, 1991). For example, Newell et al. (2001) suggested that using averaged data between subjects or between trials tended to change the individual curves. These authors showed that the mean of different exponential functions approached a power function by inhibiting different time scales (i.e., different exponents). In the same idea, King et al. (2012) recently highlighted three strategies in learning to design a 6-pointed star. The aim for the learners was to increase their score by improving both the accuracy of design and the needed to draw it. Although all learners active sought mastery of the task, the authors found that they used three types of strategies. One strategy was called "maintain speed" and in this group the

⁵ The biomechanical degrees of freedom represent the degrees of freedom of each joint independently, whereas the dynamical degrees of freedom represent the degrees of freedom of a coordination (i.e. of many joints functionally coupled)

learners explored spatially, but very little or not at all in terms of time (i.e., they increased their score by increasing accuracy). In contrast, a second strategy of "maintain accuracy" typifies a group that explored temporally, but very little if at all spatially (i.e., they increased their score by increasing the speed). A final "mixed" strategy was used by a group that explored both spatially and temporally (i.e., they increased their score by trying to increase the speed and accuracy). Although these results did not reveal the nature of exploration at a deeper level, they highlighted inter-individual differences in the temporal dynamics of learning.

In addition, taking into account only performance data (at least, the results of action) limits the generalization of such a learning law; notably, transitions in behavior imply temporal scales in addition to the performance dynamics (Liu, Mayer-Kress, & Newell, 2006, 2010, Newell & Liu, 2012). In this regard, Newell et al. (2001) initiated a field of research to determine the different time scales of learning. Indeed, the authors revisited the original data of Snoddy (1926) and hypothesized the existence of both rapid change with practice, as well as changes taking place over longer time scales (Newell et al., 2001; Newell, Mayer-Kress, Hong, & Liu, 2010), an assumption they later verified (Newell, Liu, & Mayer-Kress, 2005). Mainly, the authors described rapid changes taking place during the session ("transient adaptive") and slower changes occurring session after session ("persistent learning") (Figure 14). The emphasis on these different time scales arises from the multiple processes supporting the emergence of performance (Newell et al., 2001). Although the traditional approach conceives of a temporality corresponding to memorization processes, the identification of multiple time scales accounts for the memorization process, as well as the interaction of the learner with constraints, the trajectory of behavior in the perceptual-motor workspace, and the involvement of the different systems underlying the performance (Newell et al., 2010). Although this approach only concerns performance, it can account indirectly for several characteristics of the learning process (by adding additional time scales), such as the negative influence of fatigue during practice (Stratton, Liu Hong, Mayer-Kress, & Newell, 2007).

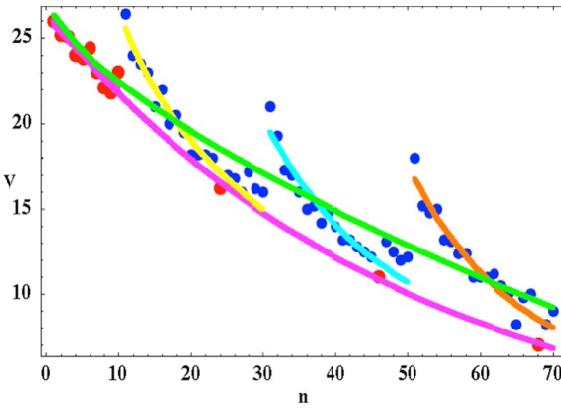


Figure 14. Time series of performance (i.e., speed decrease) at each trial (n) (based on data from Snoddy, 1926). In green, the classic mean curve taking into account all the points by a model of the power law. In yellow, blue and orange, the rapid changes operating in each session; in red, the persistent changes (best scores in each session) (Newell et al., 2005).

Performance-movement relationship. However, the process-result relationship has never really been formalized and qualitative changes in behavior are often, as in the past, inferred from changes in performance (Newell & Liu, 2012). In this regard, Delignières et al. (1998) showed that changes in coordination and performance are not the same. In a balancing task in gymnastics, novice subjects were able to improve their performance (i.e., the amplitude of the swing) without changing their behavior. The authors suggested that, despite the gradual change in performance, a discontinuity needs to occur in the behavior of novices in order for them to gain access to expert coordination. This example demonstrates the value of studying learning dynamics at different levels of analysis, such as performance and coordination, in order to better account for the nature of exploration processes (Chen et al., 2005).

A study on ski simulator showed that, with practice, modifications occurred in learners' performances (i.e., amplitude of the platform), behaviors (i.e., fluctuation of the learner's center of mass), and the learner-device relationship (i.e., relative phase between the learner's center of mass and movements of the platform), but on different time scales (Vereijken et al., 1997). In fact, the abrupt transition in the relative phase that occurred on the first day of practice was accompanied by significant changes in other variables. But while the relative phase did not change thereafter, the other variables continued to do so over the learning process. In a study on learning the ball strike in football, improved performances

with practice did not specifically occur after the emergence of a new coordination pattern (Chow, Davids, Button, & Rein, 2008). Similarly, when a decrease in performance was expected because a new coordination pattern was being used, the authors did not observe it (Chow, Davids, Button, & Rein, 2008). Liu et al. (2006) studied roller-ball learning and noted three types of response to repeated practice. After seven days of practice, the first group exhibited no change in performance or behavior. The authors assumed this was due to too little practice time. Similar to the results of Delignières et al. (1998), the second group showed an improvement in performance but no change in behavior. However, on several occasions, the individuals in this group showed an increase in behavior variability, which the authors interpreted as a strategy of exploration that could stabilize new behavior. For the third group, this increased variability led to a bifurcation in the learners' behavior, which was also associated with improved performance. In this study, behavioral changes were inferred by the acceleration of the ball; the learners began with negative acceleration but bifurcation was observed for those subjects who were able to produce a positive acceleration without paying any particular attention to the movement or limb coordination. Increased variability in the acceleration preceded the behavior change, and the authors considered this bifurcation to be a transition of the saddle-node type (Liu et al., 2006).

Nature of the transition. These assumptions about the nature of the behavioral changes that occur during learning suggest the idea of a nonlinear transition from novice to expert behavior (Newell, 1991), similar to the phase transition that operates during learning tasks in bimanual coordination (Zanone & Kelso, 1992, 1997). Nourrit et al. (2003) thus continuously analyzed the changes in behavior during a task on a monoski simulator platform over a relatively long period (i.e., 13 weeks). The behaviors of the platform were assumed to result from the participants' behavior. In this task, for which the participants had to learn to perform oscillations with the greatest possible amplitude, the authors showed a novice-expert transition through a phase of bistability. Whereas Vereijken et al. (1997) used the center of mass or the relative phase between the platform and the center of gravity, Nourrit et al. (2003) also used a more dynamic model of behavior that characterized learners' behavior as novice or expert. In fact, there seems to have been a transitional period during which novice behavior (Rayleigh damping) and expert behavior (van der Pol damping) were used alternatingly, sometimes cycle to cycle (Figure 15), with relatively low stability for the two behaviors (i.e.,

high variability). The transition from novice to expert behavior did not occur abruptly in this case, but over a period of up to several weeks, without the appearance of an intermediate behavior (Nourrit et al., 2003).

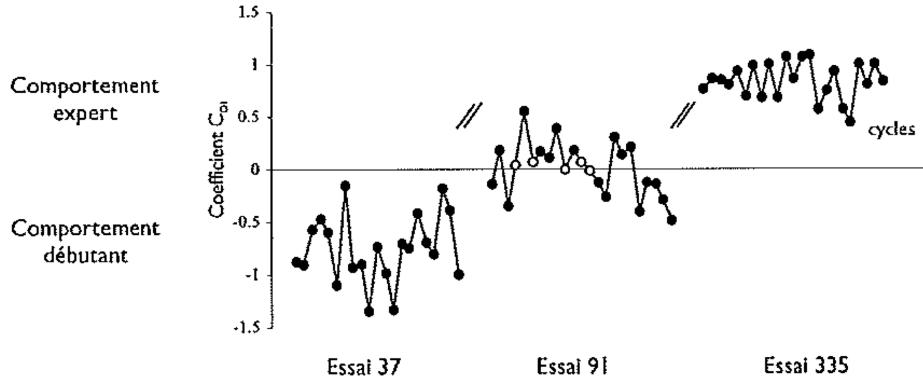


Figure 15. Cycle to cycle analysis of swinging on a ski simulator at the start (37th attempt), during (91st attempt), and at the end of learning (335th attempt). The median sample is typical of the transition phase: the subject alternates between the two typical behaviors often from one cycle to the next (Teulier & Nourrit, 2008).

In this experiment, the transition from a novice monostable regime to an expert monostable regime occurred by transition through a bistable regime. This bistable regime appeared for all five participants at about the same time, the fifth session, while its duration was variable, between 5 and 20 sessions depending on the subject. Again, the authors noted that gains in performance (characterized here by the platform amplitude) appeared before the qualitative change in behavior (i.e., between sessions 1 and 3).

The authors characterized the novice-expert transition as a *saddle-node* type, similar to the walk-run transition observed by Diedrich and Warren (1995) and proposed by Liu et al. (2006, 2010) for learning roller-ball. However, in the walk-run transition, and more generally when the transition takes place between two attractors already in the individual's repertory, it occurs abruptly (Diedrich & Warren, 1995; Kelso 1995) and is called first-order. In contrast, when a new pattern is being acquired, it is not immediately available but will in fact be constructed little by little during the transition, which means a more gradual transition including a long phase of bistability (Nourrit et al., 2003). This second-order transition is characterized by a relatively long but critical state of opaqueness. These results were recently validated by Teulier et al. (2006), who also showed that the time that

learners needed to enter a bistable regime depended greatly on the relationship between task difficulty and their skill level. Indeed, while novice behavior persisted for about five sessions on a monoski simulator, it lasted on average for only one session on a traditional ski simulator (considered as less restrictive because the feet move independently). These results reaffirm the importance of the learner's initial level, and thus the degree of competition between the intrinsic dynamics and the pattern to be learned.

Moreover, by highlighting the bistable phase of learning, these monoski simulator studies raise questions about workspace exploration. Indeed, learning in this situation seems to be a matter of stabilizing an expert pattern, yet without a real search for the pattern, as if the learners knew in advance in which direction they should be heading. In fact, the more or less restrictive nature of the task thus also appears as a factor with strong influence on the learning dynamics. In other words, some tasks generate a highly constrained workspace that intrinsically guides learners' behavior toward a mandatory solution. In contrast, other tasks have a less restrictive workspace that allows for the use of many strategies to find the optimal solution. In this sense, ski simulator tasks leave little room for exploration in that they restrict the possible movements by reducing the available degrees of freedom (i.e., foot positions fixed, movements performed in a single plane). These tasks may thus seem very restrictive compared with a football strike or swimming, for example, which leave more opportunities for exploration.

In order to be sure they could study the earliest changes in learning behavior (and thus exploration), Teulier et al. (2007) asked individuals learn to be as smooth as possible when balancing laterally; they further ensured that the subjects had no experience with the task, or even similar tasks (e.g., skiing, skateboarding, etc.). The authors described a decrease in the consistency of behavior while they were learning, meaning a loss of stability, from the moment they entered a period of bistability and *saddle-node* transition. Based on the description of Kelso and de Guzman (1991), Teulier et al. (2007) compared this transition period to a period of *intermittency*, i.e., a period of both stability and instability which has been termed *metastability* (Kelso et al., 2012; Kelso, 1995). In this case, the transition does not occur through bistability but through metastability, with relative stability/instability. More specifically, as a simple tendency toward stability, the metastable regime lets individuals circumvent the limits of their behavioral repertoires; that is, escape the initial stability of their intrinsic dynamics.

Indeed, it seems that during learning, the learner can explore different coordinations with relatively low stability (Chow, Davids, Button, & Rein, 2008). In this way, learners can freely explore the perceptual-motor workspace and access other coordination patterns in order to assess their relevance. These experiments from Teulier et al. (2007) and Chow et al. (2008) partially confirmed the results of Nourrit et al. (2003) about the nature of transition, but the order parameters they used (i.e., discrete relative phase and cluster analysis) allowed them to go further and consider the possibility of the metastable period during the transition (whereas the Rayleigh/van der Pol models imposed a binary definition of behavior and thus a bistable regime). A period of metastability suggests the emergence of several patterns, all relatively unstable with regard to their temporal occurrence, and thus a real exploration strategy, as shown in Figures 16 and 17. Again, these studies showed very different results depending on the subject and highlight the many strategies that operate during motor learning (Chow, Davids, Button, & Koh, 2008; Chow, Davids, Button, & Rein, 2008).

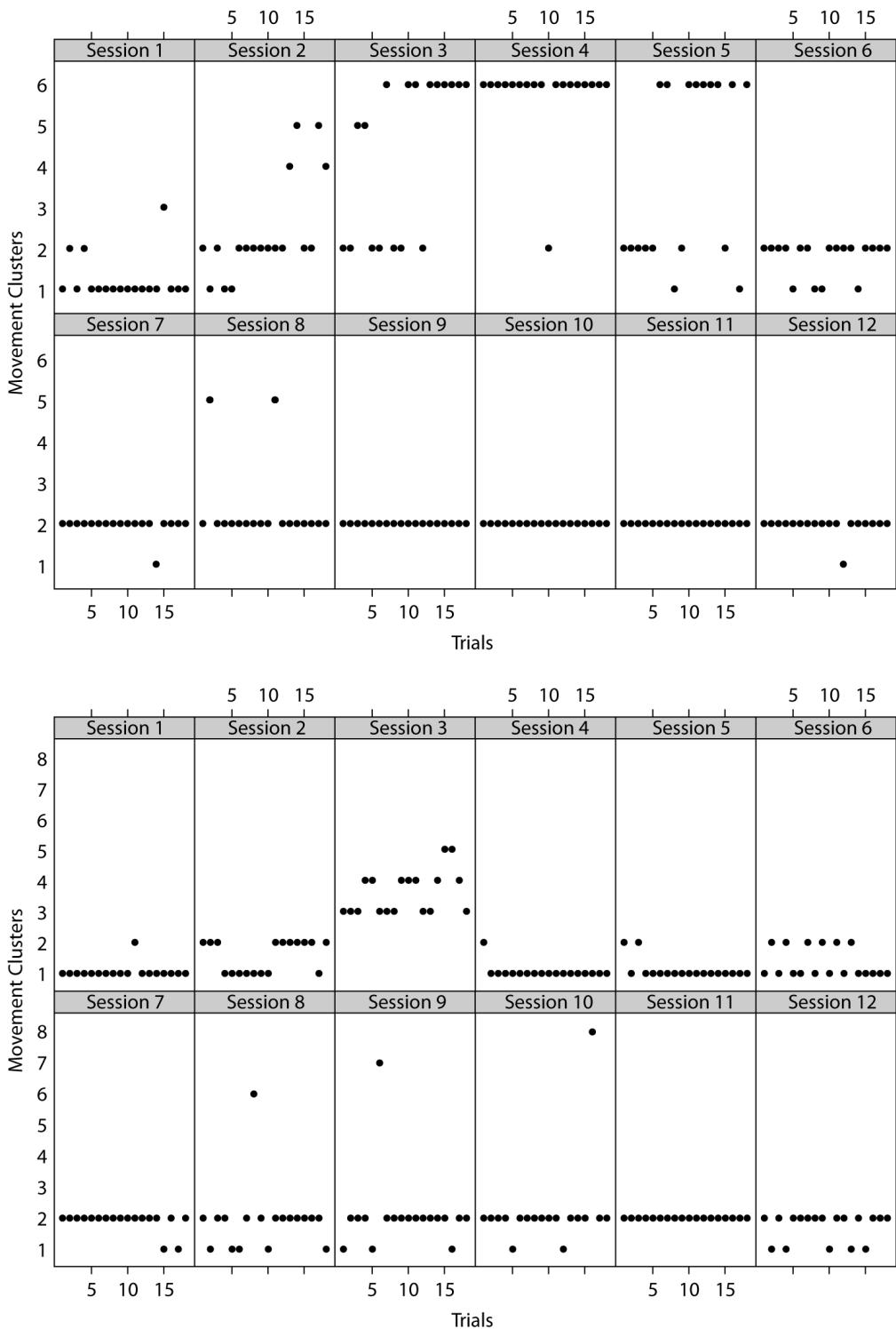


Figure 16. Analysis of the recurrence of different patterns (from 1 to 8) that learners successively adopted while learning (12 sessions) to strike a football (Chow, Davids, Button, & Rein, 2008).

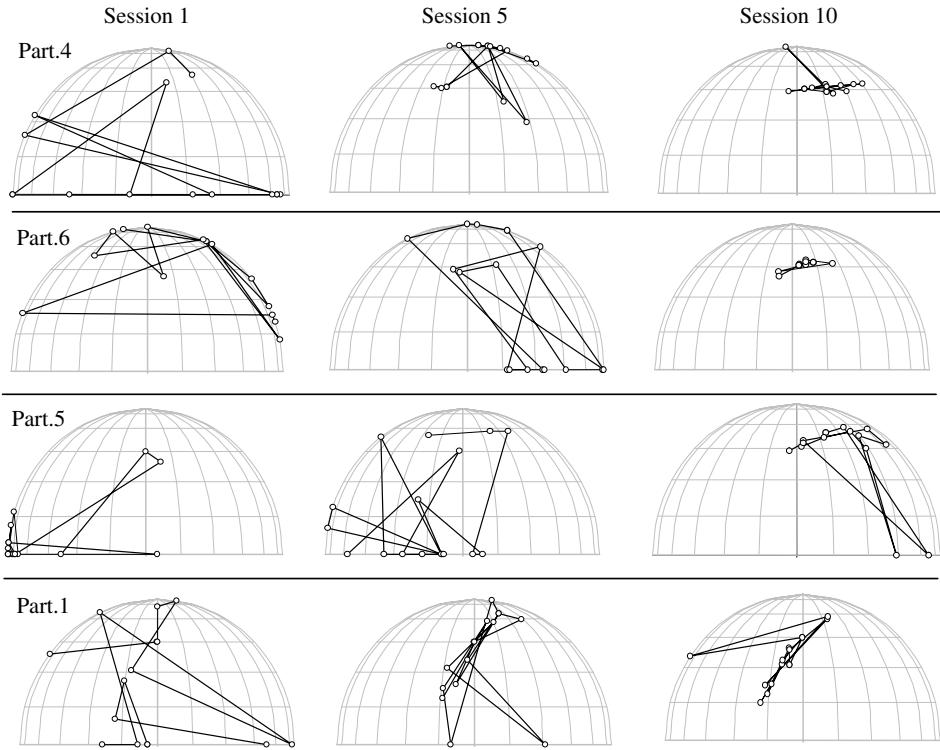


Figure 17. Spherical representation of the change in behavior forcing for 4 participants (4 lines) while learning lateral balancing (first session on the left, median session in the center, last session on the right). The half-sphere represents all possibilities: the horizontal base corresponds to forcing to the right during the swing, the half-circle represents forcing to the left during a swing, and a point in the center represents the realization of two forcings within a swing. The precise position of points on the axes represents the coordination at the moment of the forcings (Teulier & Delignières, 2007).

These studies on the nature of transitions paradoxically describe a certain "cooperation" between novice coordination and the search for expert coordination, even in so-called competitive situations (Delignières et al., 2009, p. 7). Indeed, the initial novice attractor plays a key role as a "bridgehead" (Teulier & Delignières, 2007, p. 391), a refuge attractor from which it is possible to explore and stabilize a new attractor. Chow et al. (2008) observed this result from their cluster analysis; namely, they observed that during practice, learners could use a new pattern, then return to their original pattern (sometimes for an entire session), then explore another, and so on (See Figure 16).

However, the differences in the results in terms of learning time [(e.g., transition in the first session for Veireijken, et al. [1997] and Teulier et al. [2006], after five sessions for Nourrit et al. [2003], or no transition after ten sessions for Delignière et al. [1998]) suggests that the strength of the constraints acting on

subjects during learning greatly influences their ability to leave their initial mode of coordination (Teulier & Nourrit, 2008). Teulier (2004) therefore replicated the balancing task on the parallel bars of Delignières et al. (1998) by adding a nacelle supported in part by the subjects' weight. This reduced the physical constraints, without changing the biomechanical principles of the task. The results indicated that, with a modification in the impact of the constraints, learners were able to leave their original pattern (sometimes after the second or third session) (Delignières et al., 2009), whereas earlier no change in behavior had been observed after ten sessions (Delignières et al., 1998). A learning aid would thus be to reduce the problem of movement control in relation to the impact of the constraints, without reducing the number of degrees of freedom available to allow the learner the opportunity to explore (Vereijken et al., 1997). This principle was proposed by Davids et al. (Davids et al., 2008) as *task simplification*, as opposed to the more traditional practice of *task decomposition*.

Constraints to guide exploration

The constraint-led approach (see Chapter 1) emphasizes that constraints influence performers by temporarily limiting their range of possibilities. For learning tasks, the temporary use of constraints could thus be used to guide exploration. As noted, constraints do not influence the learning process independently, but rather through their interaction, which shapes the perceptual-motor workspace of each learner (Chow et al., 2011) and limits exploration to the workspace during the acquisition process. Modifying the constraints could be used to guide the exploration of the perceptual-motor workspace, while still conserving the key variables of the information-movement coupling that regulates behavior. Guiding the perceptual-motor workspace toward a metastable state would thus facilitate the emergence of new functional coordinations during learning (Chow et al., 2011). As a system in the metastable regime expresses tendencies toward both integration and segregation, it is possible to try new organizations. This metastable regime is conducive to promoting the exploration of the perceptual-motor workspace and therefore the emergence of new functional coordination (see Chapter 1). The constraints-led approach thus underlines the critical role of verbal instructions as "temporary informational constraints" to guide exploration (Davids

et al., 2008, p. 178).

The verbal instruction as a constraint. With respect to the constraint-led approach and given that verbal instructions may function as temporary constraints to manipulate (Newell & Ranganathan, 2011), expert coordination cannot be directly *caused* by an instruction (i.e., through an accurate description of the movement), but it is possible to *exclude* certain coordination patterns as possibilities for exploration. In fact, most of the constraints presented via Newell's triangle (1986) are physical in that they reflect the properties of the individual or the environment (e.g., the shoulder anatomy that restricts possible movement). However, non-physical constraints may be equally effective and verbal instructions can be considered as temporarily guiding an emerging coordination (Newell & Ranganathan, 2011) (Figure 18).

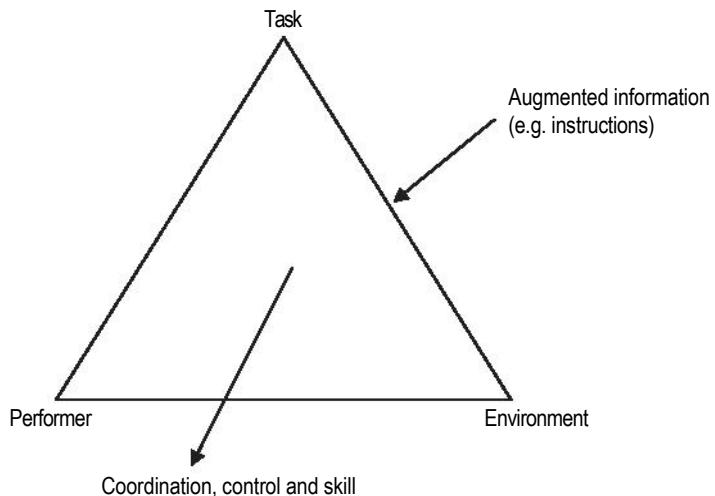


Figure 18. Representation of the constraint triangle with the addition of the role of instructions on the emergence of coordination (Newell & Ranganathan, 2011).

In fact, non-physical constraints like verbal instructions provide "intentionally used information" (Shaw, 2001, p. 299). Intention depends on many factors, such as the individual's needs, wishes and expectations, as well as external influences like instructions (Jacobs & Michaels, 2007). Intention can guide the learner's intrinsic dynamics (Scholz & Kelso, 1990), and spontaneous dynamics can be influenced by intention (i.e., specifying a pattern to achieve). In this sense, self-organization should not be seen as a "mystical" process in which the individual has no control over what he or she does. On the contrary, intention considered as "behavioral information" is a significant constraint to the system organization (Schoner & Kelso, 1988b, p. 507). Scholz

and Kelso (1990) showed that individuals were able to shift intentionally from in-phase coordination to antiphase coordination, even at oscillation frequencies above the frequency at which only in-phase coordination emerges spontaneously. Nevertheless, intrinsic dynamics seem to play an important role in the ability to intentionally alter the coordination dynamics; that is, the lower the stability of a pattern, the more quickly intention will allow a transition to another pattern, and vice versa (Scholz & Kelso, 1990). Similarly, Lee, Blandin and Proteau (1996) showed that intention was a means to limit the transitions between two patterns, by delaying or inhibiting them. Even more so, intention individually defines the task to be performed (Jacobs & Michaels, 2007). It can therefore be assumed that the same instruction leads to different intentions on the part of learners. For example, in a ball interception task, it is assumed that through the instructions that are given the individual's intention is to catch the ball and not to hit it or throw it. Therefore, the first step in the learning process is the "education of intention" (Jacobs & Michaels, 2007, p. 326) in order to initiate the process of exploring the perceptual-motor workspace (Davids et al., 2012). Wulf and Weigelt (1997) showed in learning oscillations on a ski simulator that giving a verbal instruction considerably limited the improvement in performance compared with what occurred in a group that did not receive instructions. Regardless of when or where in the learning process the information is given (i.e., at the beginning or only after several sessions), it appears that additional information in practice may facilitate learning, but may also limit its effects, hence the need to focus on the nature of the information provided. Verbal instructions can thus be used as temporary constraints to direct the learner's intentions, but the function of these intentional constraints ultimately remains the shaping of information-movement coupling. Through exploration, intention directs the learner's attention, not to provide a model to be replicated, but so that it can refine the information-movement coupling (Davids et al., 2012).

Problem and hypotheses

The literature review presented in the introductory chapter indicated that motor learning is greatly dependent on the degree of competition between the initial coordination pattern and the pattern to be learned (Zanone & Kelso, 1992). The intrinsic dynamics act as a constraint on the learning process, which can influence whether the temporal dynamics of learning are abrupt or gradual. This work has focused precisely on the nature of these temporal dynamics; that is, the nature of the relationship between novice behavior and the ultimate coordination pattern to be learned. The original investigations examined the nonlinear nature of this relationship through the exploratory strategies leading up to the acquisition of a new coordination pattern. More recent studies on the temporal dynamics of behavior have emphasized this nonlinearity by demonstrating a bistable period in behavior over the course of learning (Nourrit et al., 2003; Teulier & Delignières, 2007). These studies were concerned with the dynamics of exploration during learning and focused primarily on the dynamics of free task performance, with the only instruction being to achieve the task goal (Chow, Davids, Button, & Rein 2008; Nourrit et al., 2003; Teulier & Delignières, 2007). However, although the degree of stability of the initial pattern influences the temporal dynamics, the task and environmental constraints are also likely to have an impact on the learner's exploratory behavior (e.g., by limiting, increasing or directing it) (McDonald, Oliver, & Newell, 1995). The challenges for constraint manipulation are to guide the learner's exploratory activity without inhibiting it and to determine the optimal ratio between this exploration of possibilities and the exploitation of the original behavior.

Swimming appeared suitable for studying complexity because it involves many degrees of freedom and at first glance provides a strong potential for exploration. It requires considerable practice to achieve expertise but, more importantly, swimming is performed in an environment quite different from the natural environment of humans. Indeed, this locomotion mode is ideal for investigating a supra-coordinative task (i.e., whose objective is to reach a goal and not to reproduce a pattern) that is neither completely dependent on nor completely independent of the environment. Even when a coordination pattern is not imposed (to be learned), the aquatic environment is such that the biomechanics of movement are critical due to the high environmental constraints (i.e., water density is about 700 times greater than that of air). In fact, the ability to constantly find hydrodynamic

positions to overcome resistance to forward progress is a major factor in determining the effectiveness of movement through water (Toussaint, Hollander, Van der Berg, & Vorontsov, 2000). Thus, it is not just the glide times when the limbs are not moving that determine efficient movement, but rather the entire cycle in which the swimmer is constantly organizing and reorganizing to reach the best hydrodynamic position at a given moment (i.e., both arm and leg propulsions and recoveries). It is thus logical to assume that expert patterns exist and are characterized by biomechanical efficiency and complex organization with a high potential to accumulate and execute explicit rules. Yet the existence of such patterns raises questions about both the role of exploration in highly constrained activities and the value of exploration in the course of learning a specific and predetermined pattern.

The general objective of this work was to study the temporal dynamics of learning in terms of both movement and the resulting performance, which implies the study of movement variability and performance on different time scales (e.g., trials, sessions). In addition, the scientific challenge was to determine how to encourage exploratory behavior by changing the constraints on learning, as well as to determine the mechanisms by which exploratory behavior maximizes learning (i.e., in terms of the efficiency and/or stability of the learned pattern). The ultimate goal will be to strike an optimal compromise between exploitation and exploration by modifying task constraints during the learning process. In fact, it is the more or less implicit valence of the instructions given to learners that are key to achieving the best compromise. Our working hypothesis was that a specific modification in the task constraints to promote implicit learning would result in an increase in behavior variability, manifesting as periods of metastability.

The first objective was to investigate the nature of expertise in breaststroke and the pattern to be learned. In other words, what is the nature of expert breaststroke coordination? We conducted a cohort study and expected the characteristics of an expert pattern to emerge, with “expert” defined as a pattern that is both stable and functional (i.e., effective and efficient), but also flexible enough to respond to the constraint dynamics that swimmers experience.

Second, the value of exploring different coordination patterns was investigated in an attempt to highlight the degenerative nature of breaststroke coordination (i.e., can different patterns be used to achieve the same task goal?). The aim was not to challenge earlier findings by concluding that there is no single biomechanically efficient expert pattern, but rather to show the role of exploration in learning to

perform a task. The hypothesis was that swimmers situated between the coordination stage and the control stage may exhibit different overall patterns (i.e., coordination), while still showing the same performances at the local level (i.e., result of the pattern).

The third objective was to show how verbal instructions can be used as temporary constraints to guide exploration and maximize learning. More specifically, the use of an analogy with an internal focus (i.e., the shape of the movement) was tested with regard to its beneficial effects on learning a new coordination pattern while leaving room for exploration. The main hypothesis was that this type of analogy can generate a reorganization in the learner's coordination pattern in the direction of greater efficiency. In fact, we assumed that an internal focus, from the moment it provides only microscopic information on a macroscopic aspect of movement, can help guide learners in their search for optimal solutions through respect for degenerative nature of coordination.

To conclude, the temporal dynamics were studied to shed light on the role of exploration during motor learning and to determine how its nature can be influenced by the use of instructions as temporary constraints. The hypothesis was that the use of implicit conditions would help guide exploration and optimize learning. In fact, it is likely that a task that imposes few demands will increase the duration of the exploration phase because it allows for more exploration. However, the communication of pertinent information during learning could help to limit the workspace and thus narrow the exploration to ensure that it is optimal. In addition, a metastable regime should be reflected by an increase in the variability of coordination patterns exhibited during learning. Last, a high number of patterns explored and a significant amount of variability exhibited during the learning process can be assumed to lead to better performance (i.e., a more stable or more effective pattern) compared with a situation showing little exploration and little variability.

EXPERIMENTAL APPROACH

Chapter 3: Do qualitative changes in inter-limb coordination lead to effectiveness of aquatic locomotion rather than efficiency?

This chapter is based on the following article:

Komar, J., Sanders, R., Chollet, D, Seifert, L. (accepted) Do Qualitative Changes in Inter-limb Coordination Lead to Effectiveness of Aquatic Locomotion rather than Efficiency? Journal of Applied Biomechanics.

Analysis of arm-leg coordination when swimming breaststroke has shown that experts were able to dissociate arms and legs in order to achieve a streamlined position of one pair of limbs while the other pair propels (Leblanc, Seifert, Baudry, & Chollet, 2005; Seifert, Leblanc, Chollet, & Delignières, 2010). Conversely, recreational swimmers partially or totally superposed contradictory phases (i.e., leg propulsion during the arm recovery and arm propulsion during the leg recovery) or partially superposed arm and leg propulsions (Leblanc et al., 2005; Seifert et al., 2010). These authors suggested that the superposition of contradictory phases exhibited by recreational swimmers was not efficient because each propulsive action is thwarted by a recovery action (Leblanc et al., 2005). The superposition pattern of coordination was exhibited by recreational swimmers regardless of the swim speed. The swim speed has been shown to act as a task constraint on inter-limb coordination, or more precisely on the variability of the timing of the phases within the cycle of elite swimmers (Leblanc et al., 2005). Elite swimmers used a superposition pattern of coordination by partially overlapping the end of leg propulsion with the beginning of the arm propulsion at high swim speeds. This partial overlap of propulsive action was supposed to allow the maintenance of a high average swim speed (Seifert & Chollet, 2005). Globally, the lower the swim speed, the greater the glide time between arm and leg propulsion (Leblanc et al., 2005). Three types of arm-leg coordination (i.e. *superposition, opposition* and *glide*) were defined principally based on the duration of the time gap existing between propulsive actions of the arms and legs and depending on the swim speed. Investigating the arm-leg coordination with continuous relative phase, Seifert et al. (2010) highlighted the higher intra-cyclic variations of arm-leg coordination of experts in comparison of recreational swimmers. Experts were able to

transit from anti-phase to in-phase to anti-phase pattern within a single stroke cycle, whereas recreational swimmers mainly remained in in-phase coordination. These results suggested higher flexibility of coordination of experts.

Long duration of a glide between arm and leg propulsion has been associated with high decrease of swim speed after leg propulsion (Leblanc, Seifert, Tourny-Chollet, & Chollet, 2007), therefore leading to high intra-cyclic velocity variations (IVV) of the centre of mass (Takagi, Sugimoto, Nishijima, & Wilson, 2004). These IVV assume sizeable proportions explained mostly by the underwater recovery movements of arms and legs against the water flow that cause resistive forces (Leblanc et al., 2007; McElroy & Blanskby, 1976). These large IVV have been associated with great energy expenditure (Vilas-Boas, 1996). Nigg (1983) estimated that 10% of changes in velocity within a stroke cycle resulted in an additional work demand of 3%. Recently, Leblanc et al. (2007) showed that elite breaststrokers had higher intra-cyclic velocity variations than recreational swimmers for the same task. This seems contrary to the hypothesis that expert behaviour exhibits higher efficiency than recreational (Sparrow & Newell, 1998; Sparrow, 1983). However, there is a need to investigate whether higher IVV exhibited by experts (i.e. lower efficiency) to achieve higher effectiveness of their propulsive actions despite the possibility that this could lead to high IVV. In other words, can increased IVV be justified in terms of greater effectiveness of coordination?

The purpose of this study was to compare inter-limb coordination and indicators of swim efficiency (i.e. IVV) and swim effectiveness (i.e. peak acceleration, velocity and distance covered) between expert and recreational breaststrokers. It was hypothesized that the specific, highly constraining nature of the aquatic environment leads to the existence of a mechanically effective pattern. Namely, the inevitable deceleration of the body center of mass during the underwater arm and leg recovery leads swimmers to adopt a specific coordination to maximize propulsions. Therefore, expert swimmers would appear ‘more effective’ (i.e., generating higher acceleration) rather than ‘more efficient’ (i.e. limitating IVV) compared to recreational swimmers.

Methods

Participants

Eighteen swimmers representing two distinct levels of expertise participated voluntarily in the experiment. Performance level was their best performance for 50m breaststroke expressed as a percentage of the current world record (W.R.). Eight participants, three women and five men, composed an expert level group (20.8 ± 2.1 years; 69.7 ± 4.1 kg; 1.77 ± 0.06 m height; time done the day of the test in 25 m: 16.59 ± 1.11 s; best performance in 50 m 31.25 ± 1.49 s or 91.5 ± 3.5 %W.R.) and 10 participants, four women and six men, composed a recreational level group (20.4 ± 1.5 years, 66.0 ± 4.8 kg, 1.73 ± 0.07 m height; time done on the day of the test in 25 m: 24.44 ± 2.75 s; best performance in 50 m: 38.89 ± 4.41 s or 65.80 ± 7.75 %W.R.). The protocol was approved by the University ethics committee and followed the declaration of Helsinki. It was explained to the swimmers who then gave their written informed consent to participate. Black body markers were placed on the anatomical landmarks of the wrist (radiocarpial joint), elbow (ulnohumeral joint), shoulder (humeral head), hip (greater trochanter of the femur), knee (tibiofemoral joint) and ankle (talocrural joints) of the right side of the participants (Figure 19).

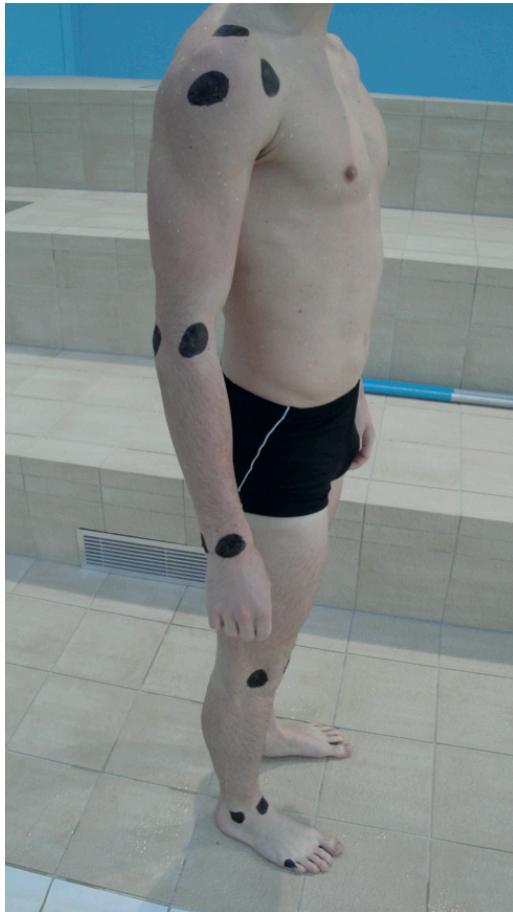


Figure 19. Placements of body markers on the right side of the swimmer.

Protocol design and video recording

Following a moderate intensity individual warm-up, the individuals were asked to perform two swims of 25 m at maximal speed in a 25-m indoor pool. After 10 minutes rest, individuals were asked to perform four trials, each consisting of a 25m swim followed by five minutes rest between trials. Two trials were performed at 90% of their maximal speed and two trials at 70% of their maximal speed. The speed of each submaximal trial was determined based on the maximal speed reached during the two previous maximal trials. For the submaximal trials, swimmers were asked to self pace the target time during the 25 m swims. The order of speed conditions was randomized across participants. During the test, mean speed of the swimmers between 5-20 m of the 25 m was assessed and a $\pm 5\%$ error was accepted to validate the time of the trial. Individuals were required to re-perform this trial if they were too slow or too fast to ensure recording of two valid trials for each swim pace.

A calibration frame of 4.5 m in the horizontal-axis (X), 1.5 m in the vertical axis (Y) and 1 m in the lateral axis (Z) was positioned in the middle lane of the pool, approximately 5 m away from the finish wall. The swimmers were then recorded in the calibrated space between 15-20 m of the 25 m swim (Pscharakis, Sanders, & Mill, 2005). Two above-water and four underwater cameras (JVC KY32 CCD, 50 Hz) were positioned around the calibration frame according to previous experiments (Pscharakis et al., 2005) (Figure 20).

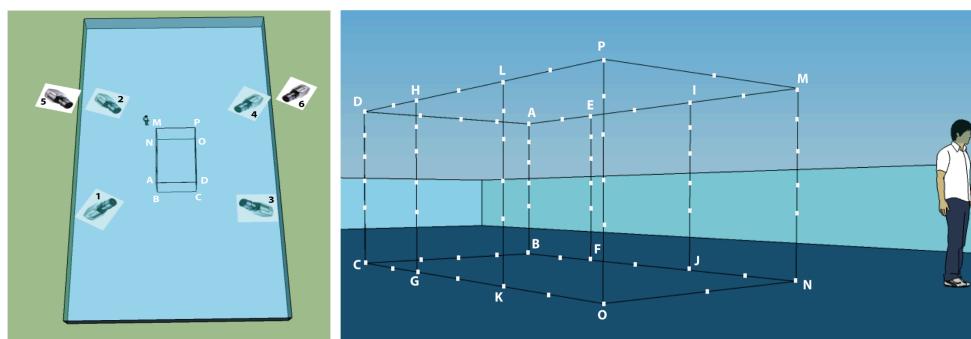


Figure 20. Positioning of the six cameras around the calibration frame (left) and capture of the view of the calibration frame from the camera 4 (right).

One stroke cycle corresponded to the period from one maximal knee flexion to the next maximal knee flexion. Video cameras recorded one stroke cycle per swim taken in the central part of the pool. Fields of view of the cameras were overlapped to ensure that all the body markers were within the view of at least two cameras at any

time. All six views were corrected for distortion (Figure 21).

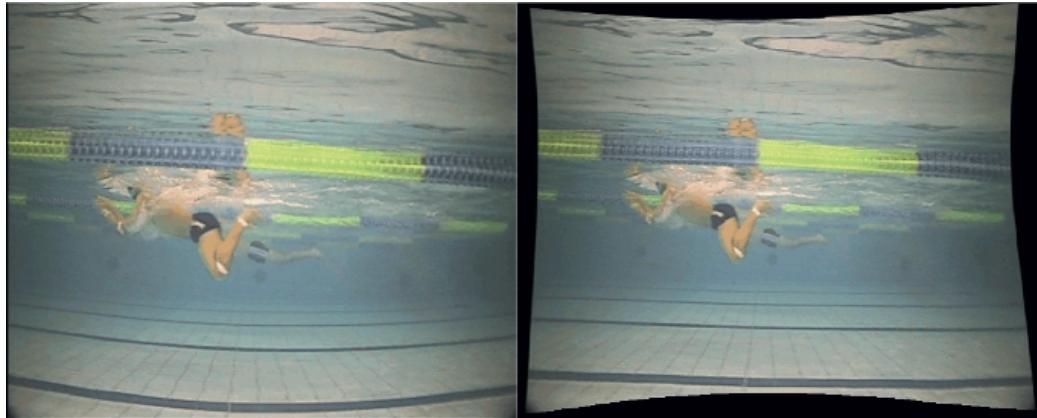


Figure 21. Example of the correction of distortion for one of the cameras: before (left) and after (right) correction.

Angle measurements and Arm-Leg coordination

Digitisation of body markers on video data allowed 3-D reconstruction of body markers using APAS software (Ariel Dynamics) and allowed the calculation of relative elbow and knee angles (error of digitizing was assessed by calculating the root mean square (RMS in cm) and the coefficient of variation (CV in %) of 10 digitisations of the same individual). Angular displacements were calculated as the arctangent of the dot product of the limb unit vectors of two adjacent limbs. Standard corrections for quadrant were applied in order to ensure angles were correct and continuous. Angular velocities were then computed as the first derivative of the angular position using the central difference formula.

Arm and leg coordination was assessed using continuous relative phase (CRP, in degrees) between two oscillators (i.e. elbow and knee angles). In accordance with Hamill, et al. (2000), the data on angular displacements (θ_{norm}) and angular velocities (ω_{norm}) were normalised in the interval [-1, +1]. Knee and elbow angles were filtered using a low-pass Fourier filter (cut off frequency 6 Hz). Phase angles (ϕ_{elbow} and ϕ_{knee}) in degrees were afterward calculated (see equation 1, Hamill et al., 2000) and corrected according to their quadrant:

$$\phi = \arctan(\omega_{\text{norm}} / \theta_{\text{norm}}) \quad [1]$$

Finally, the CRP for a complete cycle was calculated as the difference between both phase angles (equation 2, Hamill et al., 2000):

$$\text{CRP} = \phi_{\text{elbow}} - \phi_{\text{knee}} \quad [2]$$

Theoretically, two extreme modes of coordination are possible: in-phase ($CRP = 0^\circ$) and anti-phase ($CRP = 180^\circ$); however, following previous studies on inter-limb coordination, a lag of $\pm 30^\circ$ was accepted to define the adopted coordination mode (Bardy, Oullier, Bootsma, & Stoffregen, 2002; Diedrich & Warren, 1998; Seifert et al., 2011). Therefore, an in-phase mode was assumed to occur when $-30^\circ < CRP > 30^\circ$, while an anti-phase mode was defined by $-180^\circ < CRP > -150^\circ$ and $150^\circ < CRP > 180^\circ$. The first CRP value of the cycle defines the capability of the swimmers to synchronise knee flexion with arm extension. A value close to -180° (i.e. anti-phase relationship) indicates that the elbows are at their maximal extension when the legs are at their maximal flexion starting their extension. A value closer to 0° indicates that the elbows are flexed when the knees are at their maximal flexion. The time spent in-phase corresponds to the total percentage of cycle duration spent in in-phase subtracted by the time spent with arms and legs outstretched. This in-phase coordination indicates an identical motion of both arms and legs (i.e. flexion of both pairs of limbs or extension of both pairs of limbs). Therefore, it indicates how the swimmer superposed contradictory actions (i.e., leg propulsion during arm recovery or leg recovery during arm propulsion). The maximal peak of CRP identifies the period when the legs lead the arms in flexion or extension (e.g. legs are early recovering when arms are extended).

Calculation of stroking parameters and indicators of swim efficiency

Several indicators were selected to assess the swim effectiveness (Leblanc, Seifert, & Chollet, 2010; Leblanc et al., 2007): (i) Maximum velocity of the centre of mass (CM) achieved at the end of leg propulsion (Max_{Leg}), (ii) Maximum velocity of CM at the end of the arm propulsion (Max_{Arm}), (iii) Minimum velocity of CM during the transition between arm and leg propulsion ($Min_{Transitional}$), which corresponds to velocity of CM while the body glides in fully extended position, (iv) First minimum peak of CM velocity (Min_{Leg}) following arm and leg recovery and corresponding to the beginning of legs propulsion, (v) Acceleration of CM during leg propulsions (i.e. between Min_{Leg} and Max_{Leg}), (vii) Deceleration of CM during the glide (i.e. between Max_{Leg} and $Min_{Transitional}$), (viii) Acceleration of CM during arm propulsions (i.e. between $Min_{Transitional}$ and Max_{Arm}), (ix) Deceleration during arm and leg recoveries (i.e. between Max_{Arm} and Min_{Leg}), (x) Distance covered by the CM during arm propulsion, leg propulsion, glide, arm and leg recoveries. The instant position of the centre of mass (CM) was based on the anatomical model adapted by de Leva (De Leva, 1996). Six anatomical points were digitized and the head was therefore

considered as fixed relatively to the trunk, the foot as fixed relatively to the shank, and the hand as fixed relatively to the forearm (McElroy & Blanskby, 1976). Instantaneous velocity and instantaneous acceleration of the CM were calculated based on the displacement of the CM in the swimming direction. The mean swimming speed (v , in m.s^{-1}) and the distance per stroke (SL, in m) were calculated for all the cycles.

The IVV of the CM was used as an indicator of swim efficiency and calculated from the following equation (3) (Leblanc et al., 2007; Vilas-Boas, Fernandes, & Barbosa, 2011; Vilas-Boas, 1996):

$$\text{IVV} = \frac{(\text{Max}_{\text{Leg}} - \text{Min}_{\text{Leg}} + \text{Max}_{\text{Arm}} - \text{Min}_{\text{Transitional}})}{v} \quad [3]$$

Statistical analysis

The two skill levels and speed conditions were compared for (i) the knee-elbow angles and CRP (elbow angle at the beginning of the cycle, knee angle during extension, elbow angle during extension, first CRP at the beginning of the cycle, maximal value of CRP, the time spent in in-phase) and for (ii) the IVV and the displacement, velocity and acceleration of the CM during each phase of the cycle (i.e. leg propulsion, body glide, arm propulsion, arms and legs recovery). Cycles were time-normalized (100%) allowing comparison and averaging between participants. The distribution was tested for normality (Ryan Joiner test) and homogeneity of variance (Bartlett test). A two-way ANOVA (skill level [expert, recreational] \times speed condition [high, low]) was conducted using SPSS Statistics 20.0. Bonferroni post-hoc tests were used to specify the differences when the interaction skill level \times speed condition was significant. Partial eta squared (η^2_p) was calculated as an indicator of effect size, considering that $\eta^2_p = 0.01$ represents a small effect, $\eta^2_p = 0.06$ represents a medium effect and $\eta^2_p = 0.15$ represents a large effect (Cohen, 1988). Alpha was set to .05 for main statistical tests, and for the test of simple effects a Bonferroni adjustment was applied to correspond to an Alpha level of .0125.

Results

The calculated error of digitizing was: in X RMS = 2.78 cm, CV = 0.5%; in Y RMS = 2.43 cm, CV = 0.6%; in Z RMS = 3.48 cm, CV = 2.15%). For both speed

conditions, the experts swam at a higher speed, and exhibited higher distance per stroke (SL) than recreational swimmers (all $P_s < .001$, with large η_p^2) (Table 1).

For both speed conditions, recreational swimmers exhibited higher values of CRP at the beginning of the cycle than experts who exhibited an anti-phase pattern ($P < .001$) (Table 1 & Figure 22). Moreover, an interaction between skill level and speed condition was found for the CRP value at the beginning of the cycle ($F(1,68) = 4.64$, $P = .030$, $\eta_p^2 = 0.06$). A post-hoc test showed that for recreational swimmers, this first value of CRP was higher at the low swimming speed than at the high swimming speed ($P = .003$).

Table 1. Performance variables and coordination variables for expert and novice swimmers at slow and high swimming speed.

Variables	High swimming speed						Low swimming speed						Statistics (main effects)							
	Expert			Recreational			Expert			Recreational			Skill Level		Condition					
	Mean	±	SD	Mean	±	SD	Mean	±	SD	Mean	±	SD	F(1,68)	P	η_p^2	F(1,68)	P	η_p^2		
Swimming Speed (m.s ⁻¹)	a,b	1.37	±	0.10	0.98	±	0.08	1.08	±	0.11	0.64	±	0.06	428.1	<.001	0.86	202.2	<.001	0.75	
Stroke Length (m)	a,b	1.81	±	0.33	1.37	±	0.26	2.78	±	0.31	1.84	±	0.30	75.6	<.001	0.53	36.4	<.001	0.35	
Time with arms and legs outstretched (% of cycle duration)	b	20.6	±	11.2	21.4	±	13.9	43.4	±	7.1	44.2	±	13.3	0.1	.778	0.01	65.3	<.001	0.49	
Time spent in phase (% of cycle duration)	a	7.6	±	4.2	16.1	±	9.1	9.2	±	3.4	16.4	±	10.4	9.3	.003	0.12	0.2	.691	0.01	
Knee angle during extension (°)	a	176.6	±	2.2	168.9	±	3.1	173.8	±	2.4	168.7	±	5.6	54.3	<.001	0.44	3.4	.069	0.05	
Elbow angle during extension (°)	a	169.2	±	6.6	157.9	±	10.3	169.3	±	4.2	154.2	±	6.9	54.6	<.001	0.45	0.9	.331	0.01	
Elbow angle at the beginning of the cycle (°)	a,b,c	167.8	±	6.2	119.5	±	26.9	†	167.9	±	3.9	101.2	±	22.8	163.8	<.001	0.71	4.0	.048	0.06
Relative Phase at the beginning of the cycle (°)	a,b,c	-174.6	±	6.2	-119.6	±	38.2	†	-170.9	±	6.1	-93.5	±	30.1	125.2	<.001	0.65	7.7	.008	0.10
Maximal value of Relative Phase (°)	a,b	-0.3	±	10.9	37.8	±	17.2	18.5	±	14.2	53.9	±	19.1	94.3	<.001	0.58	21.3	<.001	0.24	

Note: **a** indicates a significant difference between Expert and Recreational at $P < .05$; **b** indicates a significant difference between high and low speed condition at $P < .05$; **c** indicates a significant interaction between skill level and condition at $P < .05$; **†** indicates a difference between low and high swim speed only for recreational

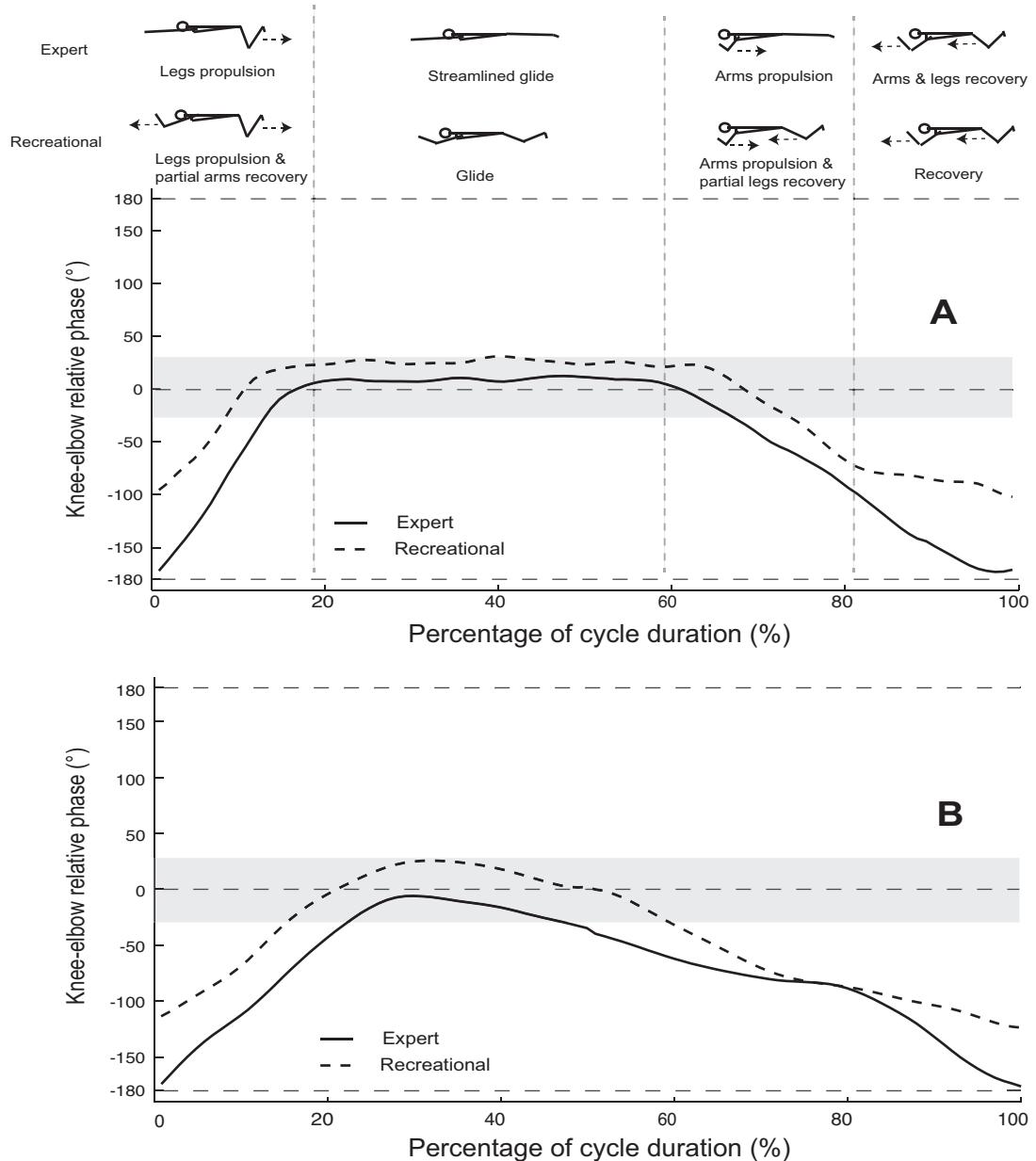


Figure 22. Mean patterns of continuous relative phase for expert swimmers (continuous line) and novice swimmers (dotted line), at 70% of their maximal speed (A) and 90% of their maximal speed (B).

For both speed conditions, experts showed an earlier outstretched position of the arms at the beginning of the cycle (i.e. close to 180°) while recreational swimmers started their cycle with their elbows flexed (i.e. close to 110°) ($P < .001$; with large η_p^2) (Table 1 & Figure 22). Moreover, an interaction effect occurred ($F(1,68) = 4.22$, $P = .041$, $\eta_p^2 = 0.06$) and post-hoc test showed that recreational swimmers were more streamlined at the high swimming speed than at the low swimming speed ($P = .020$).

Results also showed higher maximal values of CRP for recreational swimmers. This maximal value of CRP is positive for novices whereas it is close to 0°

for experts ($P < .001$, with large η_p^2) (Table 1 & Figure 22). This result highlighted that experts were capable to reach a streamlined position during the glide phase and the propulsive phase of the arms, whereas the elbow and knee joints of recreational swimmers remained slightly flexed.

No differences were found in IVV between expert and recreational swimmers, but for both skill levels, IVV appeared smaller at the high swimming speed than at the low swimming speed ($P < .001$) (Table 2). Experts exhibited a higher velocity peak as well as a higher acceleration and deceleration peak compared to novices (all $P_s < .001$). These velocity, acceleration and deceleration values were greater at the high swimming speed than at the low swimming speed (all $P_s < .001$), except for the deceleration occurring after the leg propulsion (i.e. during the glide phase) which was not dependent on the swimming speed. Experts covered greater distances during each phase of the cycle (all $P_s < .020$), except during the glide phase in the high speed condition. An interaction between skill level and speed condition occurred for the distance covered during the glide phase. Post-hoc tests showed that the distance covered during the glide phase was lower at the high swimming speed than at the low swimming speed (all $P_s < .011$), and was higher for experts than novices only at the low swimming speed ($P < .001$).

Table 2. Efficiency and effectiveness variables for expert and novice swimmers at high and low swimming speed.

Variables	High swimming speed				Low swimming speed				Statistics (main effects)							
	Expert		Recreational		Expert		Recreational		Skill Level		Condition					
	Mean	± SD	Mean	± SD	Mean	± SD	Mean	± SD	F(1,68)	P	η_p^2	F(1,68)	P	η_p^2		
Intracyclic Velocity Variations	b	0.64	± 0.18	0.69	± 0.17	0.87	± 0.17	0.80	± 0.22	0.9	.761	0.01	14.5	<.001	0.18	
Distance covered during leg propulsion (m)	a	0.39	± 0.06	0.26	± 0.07	0.40	± 0.04	0.27	± 0.06	84.6	<.001	0.56	0.5	.463	0.01	
Distance covered during leg-arm transition (m)	a,b,c	0.33	± 0.19	0.32	± 0.22	1.21	± 0.32	*	0.92	± 0.23	5.6	.020	0.08	132.1	<.001	0.67
Distance covered during arm propulsion (m)	a	0.67	± 0.06	0.55	± 0.10	0.69	± 0.09	0.40	± 0.17	17.1	<.001	0.20	1.5	.216	0.02	
Distance covered during recovery (m)	a	0.41	± 0.04	0.24	± 0.08	0.48	± 0.07	0.24	± 0.11	23.4	<.001	0.26	0.8	.365	0.01	
Maximum velocity during leg propulsion ($m.s^{-1}$)	a,b	1.54	± 0.17	1.11	± 0.15	1.33	± 0.13	0.77	± 0.11	214.6	<.001	0.76	66.4	<.001	0.49	
Minimum velocity during leg-arm transition ($m.s^{-1}$)	a,b	1.41	± 0.23	1.03	± 0.18	0.99	± 0.14	0.56	± 0.06	113.7	<.001	0.62	138.5	<.001	0.67	
Maximum velocity during arm propulsion ($m.s^{-1}$)	a,b	1.65	± 0.20	1.23	± 0.17	1.34	± 0.21	0.67	± 0.07	184.7	<.001	0.73	114.6	<.001	0.62	
Minimum velocity during recovery ($m.s^{-1}$)	a,b	0.98	± 0.17	0.58	± 0.13	0.81	± 0.12	0.40	± 0.07	185.4	<.001	0.73	36.7	<.001	0.35	
Maximum acceleration during leg propulsion ($m.s^{-2}$)	a,b	2.90	± 1.15	2.17	± 0.67	1.94	± 0.88	1.08	± 0.46	17.2	<.001	0.21	29.1	<.001	0.30	
Maximum deceleration during leg-arm transition ($m.s^{-2}$)	a	-1.01	± 0.67	-0.42	± 0.38	-0.88	± 0.38	-0.38	± 0.24	28.4	<.001	0.30	0.6	.413	0.01	
Maximum acceleration during arm propulsion ($m.s^{-2}$)	a,b	1.73	± 1.25	0.81	± 0.76	1.13	± 0.42	0.42	± 0.34	18.5	<.001	0.21	6.7	.012	0.09	
Maximum deceleration during recovery ($m.s^{-2}$)	a,b	-2.56	± 0.99	-2.17	± 0.79	-1.73	± 0.56	-0.49	± 0.22	50.8	<.001	0.43	29.9	<.001	0.31	

Note: **a** indicates a significant difference between Expert and Recreational at $P < .05$; **b** indicates a significant difference between high and low speed condition at $P < .05$; **c** indicates a significant interaction between skill level and condition at $P < .05$; * indicates a difference between expert and recreational swimmers only at low swimming speed

Discussion

The purpose of this study was to compare inter-limb coordination and indicators of swim efficiency and effectiveness between expert and recreational breaststroke swimmers. Significant differences with large effect sizes were found between expert and recreational swimmers in coordination profiles as well as in the indicators of swim efficiency. The novel finding of this study was that experts coordinated their limbs in a more effective way than recreational swimmers, but paradoxically, to the detriment of their efficiency. The following paragraphs discuss (i) how coordination is managed to minimize active drag during the glide phase by adopting a streamlined body position, (ii) how coordination is managed to maximize the speed, acceleration and horizontal distance covered by the CM, and (iii) how the maximization of propulsion influences efficiency. In addition, going further than previous studies on inter-limb coordination conducted using a 2-D video analysis (Seifert et al., 2011, 2010), the use of 3-D reconstruction provided a more accurate assessment for both elbow and knee angles which are not performed constantly in a single plane.

Coordination bras-jambe durant la glisse

This study identified that experts exhibited optimised body and segmental movements. More precisely, experts showed a better management of their arm-leg coordination during the glide phase, namely by maintaining a streamlined position with arms and legs during the glide. This non-propulsive phase is considered a key factor for performance because the fastest swimmers were found to adopt a long glide phase (D'Acquisto & Costill, 1998; Takagi et al., 2004). Results showed that the experts and recreational swimmers spent the same time with arms and legs outstretched, therefore the same relative duration of the glide. However for expert swimmers, the glide phase corresponds to an effective in-phase coupling of limbs movement (i.e., simultaneous extension of legs and arms), and varying with the swim speed (Chollet, Seifert, Leblanc, Boulesteix, & Carter, 2004; Seifert et al., 2010). Confirming this statement, in the present experiment the maximal value of CRP was close to 0° for experts at high swimming speed, corresponding to a maximally extended body position (i.e. arms and legs at their maximal value close to 180°). Even if the maximal peak of CRP still defined an in-phase coordination pattern, experts exhibited a higher maximal value of CRP at low swimming speeds than at high

swimming speeds. This result may highlight a tendency of the knee to start flexing during the glide phase when this phase is prolonged. Recreational swimmers exhibited significantly higher maximal values of CRP, meaning that the glide phase was performed with elbows and knees not maximally extended and streamlined. This was confirmed by the significantly lower values of knee and elbow angles for recreational swimmers compared to experts (Table 2). Despite a same relative duration of the glide phase, expert swimmers were more effectively streamlined during this phase than the recreational swimmers. Nevertheless, expert swimmers experienced higher deceleration during this phase. This result can be explained by the evidence of experts who exhibited lower maximal values of CRP and reached higher swimming speeds. Thus reaching higher velocities, they encountered greater forward resistance and therefore higher deceleration (considering that resistance varies with the square of the speed (Kent & Atha, 1975)). Finally, even if experts show higher deceleration during their glide phase, swimmers were still able to cover a greater distance than recreational swimmers. The segmental organization during this phase also contributes to expert swimmers achieving greater stroke lengths than recreational swimmers. At the low swimming speed, experts covered a greater distance during the glide phase, which is in accordance with previous studies (Leblanc et al., 2007). Moreover, strong correlations have been found between the distance covered by the CM during the glide phase and the total SL (0.72) (Leblanc et al., 2007), indicating that the glide phase is a major factor that modulates SL. The greater distance covered by experts during the glide phase can be explained by an effective streamlined position (D'Acquisto, Costill, Gehlsen, Young, & Lee, 1988) but also by the higher acceleration created by leg propulsion leading to higher velocity peaks (Leblanc et al., 2007). As previously shown (Seifert et al., 2010), the absence of significant differences between recreational and expert swimmers in the distance covered during the glide phase at high speed could be explained by the considerably reduced duration of the glide phase occurring when swimming fast (i.e., 21% of the cycle duration was dedicated to the glide at the high speed vs. 43% of cycle duration at the low speed).

Coordination bras-jambe durant la propulsion

In addition, experts were able to dissociate propulsive and recovery phase. Namely during the propulsive phase of one pair of limbs, they were able to adopt a streamlined position of the other set of limbs (e.g. streamlined gliding position of arms while legs are propulsive). Moreover, experts were able to synchronise the recovery phase of each pair of limbs to overcome the challenging management of

propulsive, glide and recovery phases through a cycle duration of 1 to 2 s (Chollet & Seifert, 2011). The results indicated that at high swimming speeds, experts spent less time in in-phase coupling of the arms and legs during the cycle. Experts spend less time in an iso-contraction pattern of arm and leg coordination (i.e., accordion-like (Kolmogorov, Rumyantseva, Gordon, & Cappaert, 1997; Leblanc et al., 2005) than recreational swimmers. This accordion-like pattern is known to be a basic behaviour (notably adopted in bimanual coordination task (Baldissera, Cavallari, Marini, & Tassone, 1991; Swinnen, 1997).

Expert swimmers exhibited a specific coordination leading to higher peak of acceleration than recreational swimmers. These higher peaks of acceleration led experts to higher average swimming speeds. The maximal value of CRP appeared higher for the recreational swimmers, whilst expert swimmers were close to 0°. As previously shown for a postural task (Faugloire, Bardy, & Stoffregen, 2009), when CRP is positive, the first oscillator leads the other. The maximal value of CRP was positive for recreational swimmers and revealed that the legs were leading the arms (i.e. knees were more flexed than the elbows during the beginning of the arm propulsive phase). Conversely, the 0° maximal value of CRP exhibited by experts means that the arms start their propulsion from a position where both elbows and knees were at their maximal extension, suggesting that active drag is minimized during arm propulsion. During the arm propulsion phase the CM of the expert swimmers covered a greater distance than that of recreational swimmers. According to previous studies, this greater distance was due to the higher peak velocity reached by expert (D'Acquisto et al., 1988; Leblanc et al., 2007). A strong correlation (0.76) has been highlighted previously between the distance covered by the CM during arm propulsion and the peak velocity of the CM (D'Acquisto & Costill, 1998).

Coordination et VVI

Despite a greater effectiveness of their coordination, experts do not appear more efficient than recreational swimmers. In contrast to a previous study that showed greater values of IVV for experts (Leblanc et al., 2007), there were no significant differences between the groups in the present experiment. This result could be partially explained by the use of the CM displacement rather than a speedometer as in previous experiment (Leblanc et al., 2007). The use of the CM tends to limit the extreme values of swimming velocity (Barbosa, Santos-Vila, Sousa, & Vilas-Boas, 2003), therefore impacting the calculation of the IVV. Nevertheless, both experts and recreational swimmers exhibited greater IVV during the low speed condition, mainly

due to higher deceleration related to greater time spent gliding, which is in agreement with a previous study (Leblanc et al., 2007).

Therefore, when recreational swimmers have to achieve higher speeds, they adapt both their coordination towards more effective propulsion and their glide duration. Conversely, experts do not show a different nature of the coordination between high and low speed conditions during propulsion; the adaptation resides mainly in the time spent gliding rather than in the nature of the coordination during the propulsion. Experts seem to constantly favour the effectiveness of their coordination during propulsion independently of the swim speed. Thus, the adaptation to swim speed mostly comes from a regulation of the glide time. This strategy enables experts to maintain effectiveness of propulsions and glide, but also leads to higher IVV (Leblanc et al., 2005). The fact that experts can regulate high order derivatives like acceleration to adapt to the task reflects their advanced stage of learning beyond the ‘control stage of learning’ (Newell, 1986).

Limits

The use of only six anatomical body landmarks to define the CM probably limits the accuracy of the result of the present experiment, compared to the use of a complete model with 19 landmarks. Nevertheless considering the lateral symmetry of the breaststroke swimming, the selected body segments were assumed to represent the most influential segments of the CM (i.e. the entire body except the head, hands and foots) on the X and Y axis and this method was considered as more accurate than other methods commonly used (e.g. cable velocity-meter, hip as a fixed point). Another limitation was the checking of the self-paced target speed, which was done by checking the mean speed of the swimmer and not only during the recorded cycle. This may explain the differences between the target speed (i.e. 70% and 90% of maximal speed), which was actually performed by the swimmers during the 25 m, and the speed of the CM assessed by digitizing only on the recorded cycle (i.e. the one occurring between 15-20 m of the 25 m).

Conclusion and perspectives

This study compared inter-limb coordination and indicators of swim effectiveness and efficiency between expert and recreational breaststroke swimmers. Results showed that experts did not appear more efficient than recreational swimmers. Nevertheless, experts exhibited a more effective arm-leg coordination pattern than recreational swimmers, which is the challenge of competitive swimming. Experts seemed able to use the glide duration to adapt the swimming speed, therefore

constantly preserving the effectiveness of their coordination pattern. A paramount implication is therefore the necessity for swimmers during skill acquisition to develop a specific coordination to ensure the effectiveness of their propulsions. Future research investigating the functional aspect of the glide time and the efficiency of the coordination is necessary. The question refers to the adaptation by experts of their arm-leg coordination in order to promote continuous propulsion within a cycle, therefore limiting IVV (as exemplified in Figure 23). The theoretical assumption is that a strategy that would limit the force impulse and acceleration to promote their duration and the continuity between successive force impulses is the efficient strategy in swimming (Leblanc et al., 2005). Undoubtedly, the arm-leg coordination highlights the kinematic characteristics of movement. Further investigations of kinetic parameters may help to understand better the nature of expertise in breaststroke swimming.

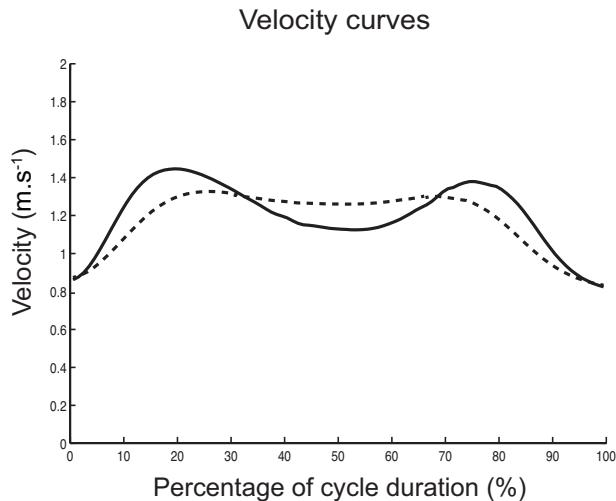


Figure 23. Mean curves of instantaneous velocity of the center of mass, actually performed (continuous line) and theoretically efficient (dotted line).

Chapter 4: Neurobiological degeneracy; supporting stability, flexibility and pluripotentiality in complex motor skills

This chapter is based on the following article:

Komar, J., Chow, J-Y, Chollet, D., Seifert, L. Neurobiological Degeneracy: Supporting Stability, Flexibility and pluripotentiality in motor learning. Under revision in *Acta Psychologica*.

From an ecological dynamical perspective (see Seifert, et al., 2013 for a review), human beings can be considered as complex dissipative structure with numerous degrees of freedom in a dynamical environment, leading to the emergence of alternative conceptualizations of processes related to perception, cognition, action and decision-making (Williams et al., 1999). The key emphasis from an ecological dynamical perspective alludes that the emergence of goal-directed behaviour is a consequence of self-organisation through the continuous performer-environment interaction (Kelso & Engström, 2006).

Recently, the study of supra-coordinative task (i.e., a task for which the goal is not to produce a specific coordination pattern, Faugloire et al., 2009) provides a suitable platform to reconsider the functional role of movement pattern variability (e.g., Hong & Newell, 2006a; Rein et al., 2010a). While movement variability is usually considered as “blameworthy when it comes to human behaviour” (Cohen et al., 2004, p. 995), there could be a need to consider potential benefits of such variability in motor control and learning (Chen et al., 2005; Hong & Newell, 2006a; Rein et al., 2010b). Indeed, while a linear approach of motor control suggests that movement variability is minimized by taking advantage of the redundancy of the motor system (Harris & Wolpert, 1998), a non-linear approach advocates that degeneracy is more appropriate in examining coordination in neurobiological systems (Newell et al., 2005). In fact, *redundancy* is only one of the multiple ways to promote *degeneracy* in complex neurobiological systems (Mason, 2010). Redundancy reflects the duplication of a system (i.e., the presence of isomorphic and isofunctional components) in order to ensure robustness in case of failure of the initial version (Mason, 2010). Conversely, the degenerate architecture of complex systems is isofunctional but heteromorphic (Mason, 2010; Tononi et al., 1999), and supports

both stability of the motor organization against perturbations, and functional variability in facing dynamical environment (Seifert et al., 2013). Specifically, neurobiological degeneracy exists at all levels of neurobiological systems (e.g., from genetic code to behavioural repertoires) and is technically defined as ‘the ability of elements that are structurally different to perform the same function or yield the same output’ (Edelman & Gally, 2001, p. 13763). But unlike redundancy, degeneracy also provides the ability to perform different functions under different conditions (Mason, 2010; Whitacre, 2010). Critically, degenerate elements may share the same function, but unlike redundant elements, they do not share the same over-all structure.

For instance, in a ski-simulator task, Hong and Newell (2006b) showed how different participants were able to use different inter-limb coordination patterns to reach the same performance outcomes. When knee motion relations were examined, both in-phase and anti-phase coordination patterns were exhibited by the participants with the presence of an effective coupling between the center of mass and the ski platform (i.e., the same effective outcome). From Hong and Newell (2006b), it was concluded that locally, different joints organization could occur although similar global function was achieved. Similarly, Rein et al. (2010a) analyzed the full-body kinematics of basketball hook shoot and reported high inter-individual differences in elbow-shoulder and knee-hip coordination during the execution of the shots at the same target distance (with distances tested varying from 2 to 9 m). In addition, Rein et al. (2010a) also highlighted multiple pathways of adaptation with reference to different throwing distances. When performance of cricket batting was investigated, Pinder et al. (2012) demonstrated how individuals exploited system degeneracy to functionally adapt stable movement pattern solutions to satisfy changing task constraints (e.g., forward or backward movements). These results provided strong empirical support for the emergence of a functional degenerate behavior in multi-articular movements. Indeed, it appears that when several movement patterns are available, learners can individually exploit the inherent degeneracy present in neurobiological systems to achieve the task goal.

In addition to ensure stability against perturbations and adaptation to dynamical environment, it is suggested that the degenerate architecture of neurobiological systems plays a central role in adaptive innovation of complex system (Hristovski et al., 2006; Whitacre, 2010). It creates the potential for variations and encourages “pluripotentiality” (Mason, 2010, p. 281). Specifically, pluripotentiality refers to the potential involvement or removal of biomechanical degrees of freedom to

increase stability or flexibility of the system. More precisely, there are opportunities for the human movement system to acquire two or more coordination patterns, sometimes partially sharing same elements (e.g., partially sharing same joints), to accomplish a task. For instance in catching a ball, one can essentially coordinate his shoulder, elbow and wrist to reach the ball, but could also move and coordinate his entire body while additionally involving his hip, knee and ankle to realize the task. This partial use of possible joints offers the possibility to always involve additional degrees of freedom into the overall coordinative structure to ensure task realization. In other words, degeneracy may allow a surplus of degrees of freedom necessary for later exaptation (Mason, 2010). Degeneracy therefore plays an important role in learning, providing the basis for the diversity of actions required to negotiate information-rich environment, as well as providing huge evolutionary fitness advantage (Seifert et al., 2013). Importantly, the acquired coordination is a product of self-organisation and the instances of exploration (i.e., variability during learning) are an inherent part of the learning process (Newell, 1991; Sporns & Edelman, 1993). Chow et al. (2008), in a soccer kicking study, further observed that there were actually no common pathways of change in coordination pattern during learning, suggesting that directional changes in degrees of freedom was dependant on task relevant intrinsic dynamics. Inevitably in the process of skill acquisition, the pathway to organize joints was different across participants, suggesting the functional role of degeneracy during learning.

One framework that could yield insights into the functional role of system's degeneracy is Newell's model of learning with three stages of learning (*coordination*, *control* and *skill*, Newell, 1985). Early in learning (i.e. between coordination and control stage) novices are challenged to seek for a functional assembling of the body parts regarding task and environmental conditions. Once reached the control stage, performers are able to perform with consistency in changing performance environment. Later during learning, skill stage is observed when performers are able to use reactive forces from their muscular-skeletal system or from the environment to efficiently achieve the task. Specifically, for learners who are navigating between coordination and control stage of learning, there is a need to progressively become more attuned to the consequences of different combinations of key variables in impacting the task behaviour. Degeneracy may therefore support the explorative activity of learners involved in the transition between those two stages (see Chow et al., 2008).

Interestingly, swimming represents a supra-coordinative task, but it is assumed that a biomechanically effective pattern of coordination between elbow and knee oscillations seems to be adopted by expert performers compared to novices (Seifert et al., 2011). For example, experts were able to start a swimming cycle with arm-leg coordination in anti-phase followed by an in-phase mode and then back to anti-phase mode through every cycle of movement (i.e., every 1-2 sec). In aquatic activities where the environmental constraints play an important role (e.g., due to high density of water), the use of a biomechanically effective pattern becomes pertinent for effective performances (Seifert et al., 2010). In addition, the level of environmental constraint (i.e., the amount of forward resistance swimmers have to overcome in order to move) is related to the swimming speed squared (see Toussaint & Truijens, 2005), therefore an increase in swimming speed leads to quadratic increase of environmental constraints. It is therefore unclear whether learners need to actively explore the perceptual-motor workspace when learning a specific biomechanical expert pattern during their transition between coordination and control stage of learning, or instead converge directly towards this biomechanical expert pattern.

This paper aims to investigate the role of neurobiological degeneracy in the acquisition of coordination in a task where the perceptual-motor workspace is highly constrained and the existence of a biomechanically effective expert pattern is assumed. More precisely, the objectives were to: i) determine if there is inherent degeneracy for a swimming task; ii) determine how the level of constraints can limit the expression of degeneracy; iii) explore how degeneracy can support a functional role for movement variability. We then hypothesized that even if the desired outcome of learning is the acquisition of a single biomechanically effective pattern, active exploration of the workspace can be facilitated by the inherent neurobiological degeneracy. In addition, it is predicted that participants who are seeking for a functional coordination (i.e., between coordination and control stage of learning, Newell, 1985) may exhibit different patterns of coordination reflecting explorative behaviours. Whereas stability and accuracy are usually the features of the movement to define an optimal learning (Tallet et al., 2008), the findings from this study may highlight the critical role played by neurobiological degeneracy and especially pluripotentiality property as a way of acquiring skill flexibility during the learning process.

Method

Participants

Fourteen breaststroke swimmers representing a range of recreational level swimmers (i.e., assessed by two experienced swimming instructors and motor control specialists as navigating between coordination and control stage of learning based on Newell's model of learning) were recruited for this study. Expertise level was expressed as a percentage of the current world record (W.R.) based on their best performance for 50-m breaststroke. Six women and eight men (18.9 ± 1.0 years, 62.2 ± 8.5 kg, 1.72 ± 0.63 m height; time measured on the day of the test in 25 m: 22.1 ± 2.5 s; best performance in 50 m: 38.89 ± 4.41 s that represents $63.70 \pm 7.25\%$ W.R.) were recruited for this study. The protocol, approved by the University ethics committee, was explained to the swimmers, who then gave their written informed consent to participate.

Task and Procedure

Participants were first required to warm up individually in a 25-m indoor pool at moderate intensity. Thereafter, the participants were asked to perform four trials, each consisting of a 25 m swim followed by 5 minutes rest between trials. The task was identical for each participant, i.e. normalized based on their personal maximal achievable speed. Two trials were performed at 90% of their maximal speed and two trials at 70% of their maximal speed. The speed of the trials was determined *a priori* and swimmers were then asked to self pace a target time during the 25 m swims. The order of speed conditions was randomized across participants. A $\pm 5\%$ error on the time realized compared to the target time was accepted to validate the trial, and participants had to repeat this trial if they were too slow or too fast, in order to establish two trials per speed condition that are acceptable for each individual.

Video recording

Black body markers were placed on the anatomical landmarks of the wrist (radiocarpial joint), elbow (ulnohumeral joint), shoulder (humeral head), hip (trochanter major of femur), knee (tibiofemoral joint) and ankle (talocrural joints) of the participants. A calibration frame of 4 m in horizontal-axis (X), 2 m in vertical axis (Y) and 2 m in lateral axis (Z) was positioned on the floor of the pool, in the middle of the pool and orthogonally to the wall. Two above-water and four underwater

stationary cameras (Panasonic NV-GS17, 50 Hz) were positioned around the calibration frame according to a previous study by Psycharakis and Sanders (2009). The six views were synchronised and genlocked a posteriori with Adobe Premiere® 6.0. Cameras videotaped one cycle per swim taken in the central part of the pool. Fields of the cameras were crossed in order to be able to view all the body markers with at least two cameras at any time. Each cycle corresponded to the period from one maximal knee flexion to the next maximal knee flexion (Seifert et al., 2010).

Movement Analysis

Angles calculation

Digitisation of body markers on video data allowed 3-D reconstruction of body markers using APAS software (Ariel Dynamics) and allowed the calculation of relative elbow and knee angles (error of digitizing was assessed by calculating the root mean square (RMS in cm) and the coefficient of variation (CV in %) of ten digitisations of the same individual: in X RMS = 2.78 cm, CV = 0.5%; in Y RMS = 2.43 cm, CV = 0.6%; in Z RMS = 3.48 cm, CV = 1.15%). Angular displacements were calculated as the arctangent of the dot product of the limb unit vector of two adjacent limbs with the standard corrections for quadrant. Angular velocities were then computed as the first derivative of the angular position using the central difference formula.

Computation of Continuous Relative Phase

As previously introduced by Haken (Haken, Kelso, & Bunz, 1985), the continuous relative phase (ϕ_{rel}) was considered as a suitable order parameter or collective variable representing the emergent organization of the multiple degrees of freedom (Seifert et al., 2011, 2010).

With reference to Hamill et al. (Hamill, Haddad, & McDermott, 2000), the data on angular displacements and angular velocities were normalised at an interval [-1, +1] as follows (see equation 4 and 5):

$$\text{Angular position: } \theta_{\text{norm}} = \frac{2\theta}{(\theta_{\text{max}} - \theta_{\text{min}})} - \frac{(\theta_{\text{max}} + \theta_{\text{min}})}{(\theta_{\text{max}} - \theta_{\text{min}})} \quad [4]$$

Where θ_{max} is the maximum angular position within one complete cycle and θ_{min} is the minimum angular position within one complete cycle.

$$\text{Angular velocity: } \omega_{\text{norm}} = \frac{2\omega}{(\omega_{\text{max}} - \omega_{\text{min}})} - \frac{(\omega_{\text{max}} + \omega_{\text{min}})}{(\omega_{\text{max}} - \omega_{\text{min}})} \quad [5]$$

Where ω_{max} is the maximum angular velocity within one complete cycle and ω_{min} is the minimum angular velocity within one complete cycle. Knee and elbow angles

were previously filtered using a low-pass Fourier filter (cut off frequency 6 Hz). Phase angles (ϕ_{elbow} and ϕ_{knee}) in degrees were subsequently calculated (see equation 6) and corrected according to their quadrant:

$$\phi = \arctan(\omega_{\text{norm}} / \theta_{\text{norm}}) \quad [6]$$

Finally, ϕ_{rel} for a complete cycle was calculated as the difference between both phase angles (equation 7):

$$\phi_{\text{rel}} = \phi_{\text{elbow}} - \phi_{\text{knee}} \quad [7]$$

Theoretically, two extreme modes of coordination are possible: in-phase ($\phi_{\text{rel}} = 0^\circ$) and anti-phase ($\phi_{\text{rel}} = 180^\circ$); however, following previous studies in inter-limb coordination, a lag of $\pm 30^\circ$ was accepted to define the adopted coordination mode (e.g., Bardy, Oullier, Bootsma, & Stoffregen, 2002; Diedrich & Warren, 1998). Therefore, an in-phase mode was assumed to occur when $-30^\circ < \phi_{\text{rel}} > 30^\circ$, while an anti-phase mode was taken to be between $-180^\circ < \phi_{\text{rel}} > -150^\circ$ and $150^\circ < \phi_{\text{rel}} > 180^\circ$. Following Seifert et al. (2011), the first ϕ_{rel} value of the cycle provides an indication about the capability of the swimmers to synchronise the start of the legs extension with regards to the end of the arms recovery. The time spent in in-phase corresponds to the total percentage of cycle duration spent in-phase subtracted by the time spent with arms and legs outstretched. It indicates how the swimmers superposed iso-directional actions (i.e., leg flexion [corresponding to propulsion] with arm flexion [corresponding to recovery] or leg extension with arm extension). The maximal peak of ϕ_{rel} indicates the period when the legs lead the arms in flexion or extension (e.g., legs are early recovering when arms are extended). Finally, the mean value of CRP across the cycle indicates which oscillator globally leads the other (i.e., a positive value indicates that knee is leading and a negative value indicates that elbow is leading).

Estimation of Movement Outcome

The instantaneous position of the center of mass (CM) was based on the anatomical model adapted by de Leva (De Leva, 1996), with the consideration that the head is fixed relative to the trunk, the foot as fixed relative to the shank, and the hand as fixed relative to the forearm. In total, six anatomical points were digitized, but considering the symmetrical movements of the breaststroke pattern, these six points were assumed to accurately represent both sides of the individuals and therefore the most influential body parts on the CM in the X and Y axis. The intra-cycle velocity variations of the CM were then calculated as the first derivative of the

displacement of the CM using the central difference formula. The intra-cyclic acceleration variations of the CM were calculated as the second derivative of the displacement of the CM using the central difference formula. For all the cycles, the mean swimming speed (v , in m. s^{-1}) and the stroke rate (SR, in Hz) were calculated.

Dependant Variables

Movement Pattern and Coordination Variables

Five indicators of coordination were derived from the CRP in order to perform the cluster analysis (Seifert et al., 2011): the time spent in in-phase, the relative phase at beginning of the cycle, the maximal value of CRP, the standard deviation of the CRP across a cycle and the mean value of CRP across the cycle. In addition, variables about independent oscillators were used to characterize the different patterns: the elbow angle at the beginning of the cycle, the amplitude of elbow motion, the maximal value of elbow across the cycle, the amplitude of knee motion, the maximal value of knee across the cycle, the maximal knee rotation speed (i.e., during extension), the minimal knee rotation speed (i.e., during flexion), the maximal elbow rotation speed and the minimal elbow rotation speed.

Movement Outcomes

Movement outcomes were defined by the mean swimming speed and stroke rate. In addition, four indicators resulting from movement organization during specific phases of a cycle were investigated (see Leblanc, Seifert, Tourny-Chollet, & Chollet, 2007): the maximal acceleration of the CM during leg propulsion (i.e., extension), the maximal acceleration of the CM during arm propulsion (i.e., flexion), the distance covered by the CM during leg propulsion and the distance covered by the CM during arm extension.

Data Analysis

Coordination Profiling

Based on coordination variables, hierarchical agglomerative cluster analysis using the squared Euclidean distance dissimilarity measure and the Ward linkage method (Everitt, Landau, & Morven, 2001) was applied to determine several profiles within this group of swimmers. Before computation, a pre-processing procedure was required and all variables were normalized between the interval [0, 1] to avoid errors due to the different scales of the measures (Rein, Button, Davids, & Summers, 2010).

Cluster Validation

According to Breiman (1996) and Rein et al. (2010), the number of clusters and classification of the participants in the clusters were validated by two procedures,

namely i) a bootstrapping procedure testing the stability of the clusters, and ii) the use of an index testing the compactness of clusters. One bootstrapping procedure was used to construct the dendrogram, and this was repeated for all participants – 1 (one excluded at the time) and determined if the obtained classifications are stable or not. For example, if participant 1 was removed from the analysis, it is critical to determine if each participant remained in his initial cluster or if there was a switch from one cluster to another cluster). The identical bootstrapping procedure was also applied to repeat the clustering with all coordination variables -1. From the bootstrapping procedure, a classification was considered as optimal when the composition of the dendrogram (number of clusters and classification of the participants in the cluster) did not change in comparison to the initial result. In addition, as no real clustering was a priori defined, an internal estimator, the index of Calinski & Harabasz (Calinski & Harabasz, 1974), was used to estimate the number of clusters that best fitted the data (Zhao & Karypis, 2005). The index of Calinski Harabasz (CH) is defined by equation 8 and was calculated for a range from two to eight potential clusters:

$$CH(k) = \frac{B(k)/(k-1)}{W(k)/(n-k)} \quad [8]$$

where n represents the number of participants, k denotes the number of clusters [2-8], and $B(k)$ and $W(k)$ denote the between and within clusters sums of squares of the partition. The maximal value of CH indicates optimal ratio between inter-cluster distance and intra-cluster distance and in turn, an optimal value of the number of clusters. All tests were conducted with MatLab r2010b.

Statistical Analysis

For all measured variables, raw time-series of all cycles were time-normalized (100%) and therefore allowing comparison and averaging within clusters. After performing the cluster analysis, and when the normality of the distribution (Kolmogorov-Smirnov test) and the variance homogeneity (Levene's test) were confirmed to be acceptable, the comparison between emerging clusters was done by one-way ANOVA (fixed factor: group) and Tukey HSD post-hoc test was used in a case of more than two groups. Partial eta squared (η_p^2) was calculated as an indicator of effect size, considering that $\eta_p^2 = 0.02$ represents a small effect, $\eta_p^2 = 0.13$ represents a medium effect and $\eta_p^2 = 0.26$ represents a large effect (Cohen, 1988). All analyses were undertaken using SPSS (SPSS Statistics 20.0, IBM) with a conventional significance level at $p < .05$.

Results

Coordination Profiling

In a weakly constrained environment (i.e., low speed condition), the cluster analysis enabled the classification of participants in four different clusters as shown in Figure 24 (Cluster 1 = P7, P13, P12 and P14; Cluster 2 = P1, P8, P9 and P4; Cluster, 3 = P5, P6 and S11; Cluster 4 = P2, P3 and P10). The CH index was the highest for this number of cluster ($CH = 3.2$). The cluster validation using the bagging procedure showed that the cluster composition changed when participant 6 was removed (switch of participant 1 from cluster 3 to cluster 4), and when participant 8 and participant 13 were removed (switch of participant 9 from cluster 3 to cluster 4). Furthermore, the cluster composition did not change when the other participants were removed one by one.

For this weakly constrained condition, each cluster differed by their arm-leg coordination at the beginning of the cycle that is by the position of their arms more or less streamlined when they began propulsion of their legs. In addition, cluster 3 is characterized by high value of CRP corresponding to periods when legs are leading the arms, and a low standard deviation of coordination during the cycle. Cluster 2 is characterized by a high amount of time spent in in-phase coordination mode, corresponding to a superposition of a large amount of contradictory actions (i.e., arms propulsion and leg recovery or arm recovery and leg propulsion) and a low standard deviation of coordination during the cycle. Conversely, cluster 4 is characterized by a large standard deviation of coordination where individuals had the tendency to switch from anti-phase mode to in-phase mode to anti-phase mode within a cycle. Cluster 1 appears most similar to cluster 4 except for the CRP value at the beginning that was lower (-150° for cluster 4 and -118° for cluster 1).

Weakly constrained environment

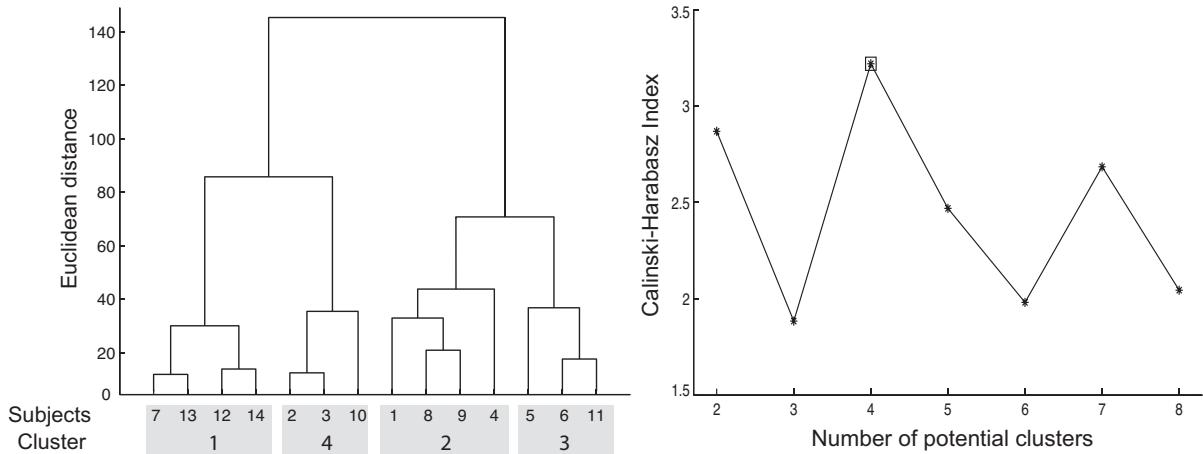


Figure 24. Hierarchical agglomerative Dendrogram (left panel) and index of Calinski-Harabasz for 2 to 8 potential clusters (right panel) in the weakly constrained environment.

More precisely, while looking at the differences in terms of coordination variables, each group appeared somehow significantly different from the others. The patterns of coordination of the four clusters presented in Figure 25 (left panel) exhibited a different value of CRP at the beginning of the cycle ($F(3,10) = 6.54, p = .010, \eta_P^2 = .662$, all $p_s < .011$ for post-hoc). Therefore, each cluster showed a different level of arm extension when knees started their extension (i.e., legs propulsion). Namely, the closer to anti-phase the first CRP value (i.e., close to -180°) is, the more streamlined were the arms when the legs began propulsion. In addition, cluster 3 is characterised by more time spent with legs leading the arms, with the maximal value of CRP appearing higher for cluster 3 than the other clusters ($F(3,10) = 5.71, p = .015, \eta_P^2 = .632$, all $p_s < .026$ for post-hoc). Similarly, the mean value of CRP was positive for cluster 3 ($M = 23.9 \pm 3.3^\circ$), when it was negative and significantly lower ($M = -17.8 \pm 7.8^\circ$) for the other clusters than cluster 3 ($F(3,10) = 9.23, p = .003, \eta_P^2 = .735$, all $p_s < .006$ for post-hoc). This cluster 3 also showed a lower standard deviation of the CRP ($37.5 \pm 0.4^\circ$) than cluster 1 ($61.3 \pm 6.1^\circ$) and cluster 4 ($74.6 \pm 10.2^\circ$) ($F(3,10) = 11.56, p < .001, \eta_P^2 = .776$, all $p_s < .020$ for post-hoc). In addition, cluster 4 also differed from cluster 2 in terms of standard deviation ($p = 0.006$). Finally, cluster 1 differed from cluster 2 in terms of time spent in in-phase ($F(3,10) = 6.54, p = .010, \eta_P^2 = .662, p < .010$ for post-hoc).

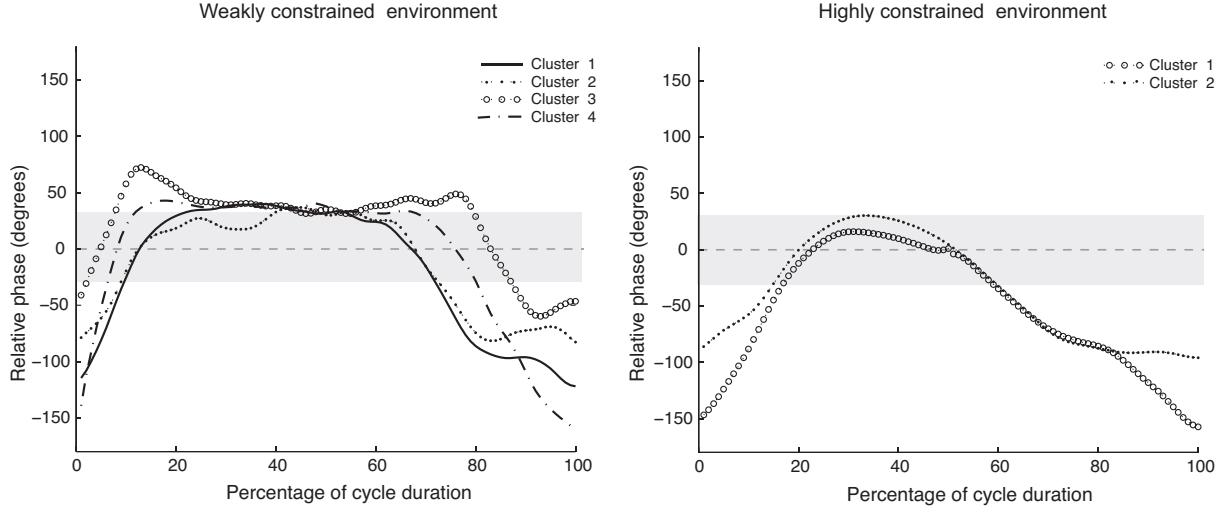


Figure 25. Mean patterns of CRP for both weakly (left) and highly (right) constrained environment (the grey zone represents the in-phase coordination mode).

In a highly constrained environment (i.e., high speed condition), the higher level of environmental constraint appeared limiting the expression of degeneracy as individuals expressed less possibility to vary their coordination. Indeed, only two different clusters in terms of the classification of performers were present from the cluster analysis undertaken and this is shown in Figure 26 (Cluster 1 = P2, P4, P14, P10, P5, P7 and P12; Cluster 2 = P1, P8, P11, P3, P13, P6 and P9). The CH index was the highest for this number of cluster ($CH = 10.5$). The cluster validation using the bagging procedure showed that the cluster composition did not change when the performers were removed one by one. In this condition, Figure 25 (right panel) showed that cluster 1 exhibited a lower value of CRP at the beginning of the cycle ($F(1,12) = 14.74, p = .002, \eta_P^2 = .575$) and a higher mean value of CRP than cluster 2 (mean CRP = $-37.1 \pm 11.1^\circ$ for cluster 1 and $-59.4 \pm 12.2^\circ$ for cluster 2) ($F(1,12) = 12.93, p = .004, \eta_P^2 = .519$). For all the other variables (i.e., time spent in in-phase, maximal value of CRP and standard deviation of CRP), no differences between clusters were found.

Highly constrained environment

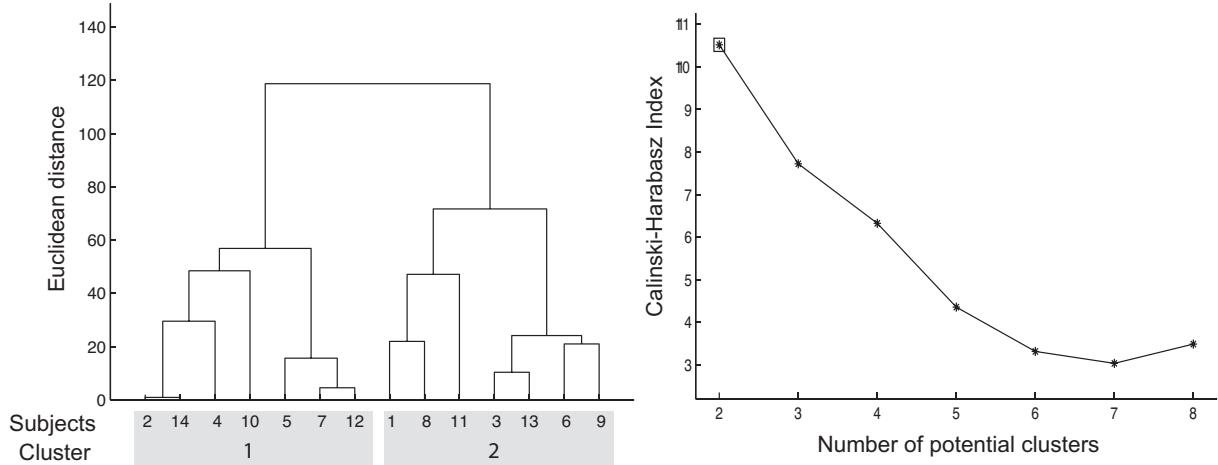


Figure 26. Hierarchical agglomerative Dendrogram (left panel) and index of Calinski-Harabasz for 2 to 8 potential clusters (right panel) in the highly constrained environment.

Movement Patterns

In addition to coordination profiling, Figure 27 and Table 3 present the characteristics of each oscillator. In the weakly constrained condition, the differences between clusters appeared mainly on the elbow rather than on the knee. Indeed, individuals exhibited a similar knee pattern in both weakly and highly constrained conditions. The only exception is the presence of a higher knee angular velocity during extension (i.e., propulsion) for clusters 3 and 4 in a weakly constrained environment ($F(3,10) = 18.81, p = .001, \eta_P^2 = .849, p_s < .048$ for post hoc) (Table 3).

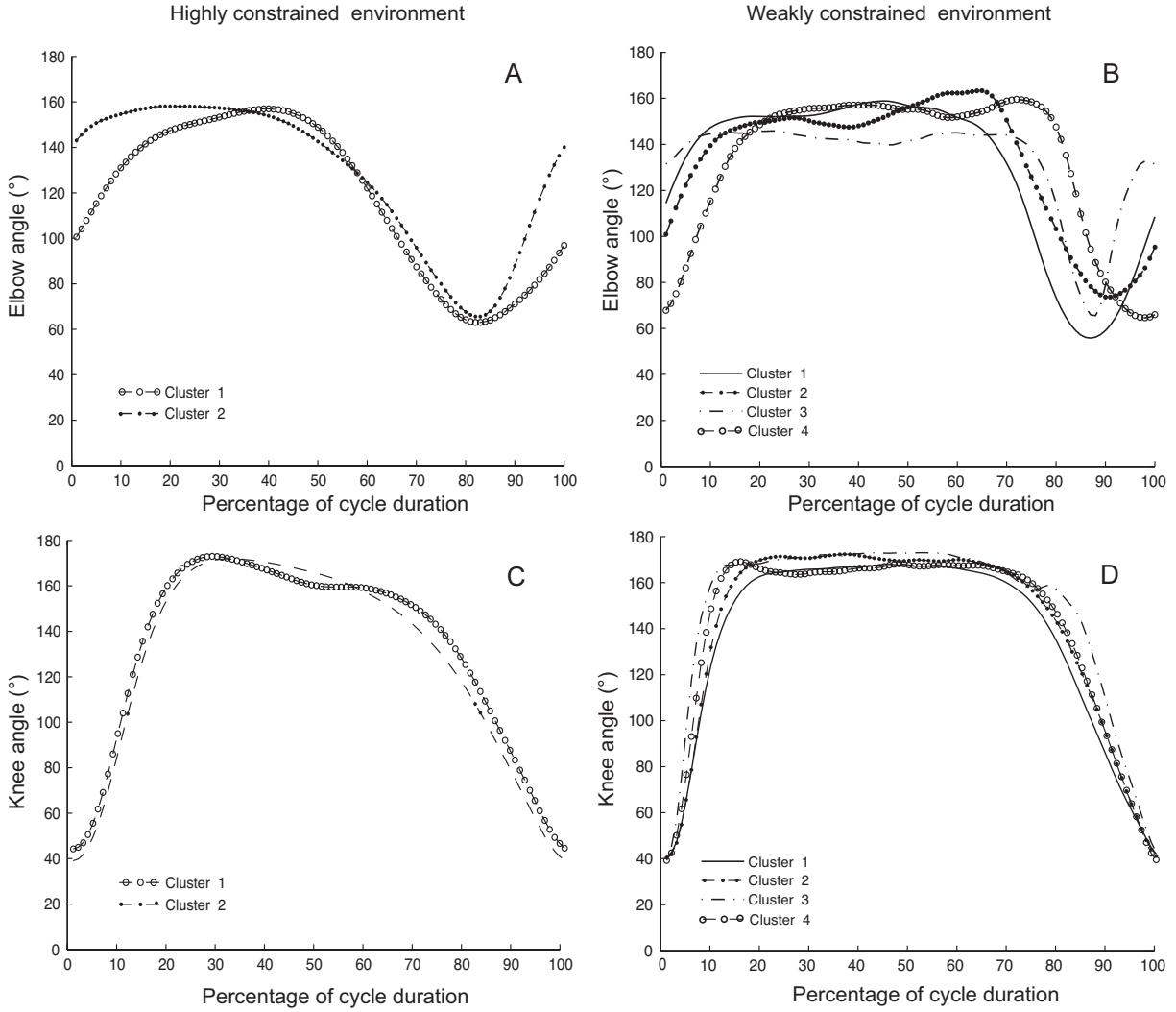


Figure 27. Mean patterns of elbow angular positions in highly constrained environment (A) and in weakly constrained environment (B), and mean patterns of knee angular positions in highly constrained environment (C) and in weakly constrained environment (D).

Conversely, clusters are differentiated by the movement pattern of the elbow that appeared as a key factor of the coordination. More precisely, in weakly constrained environment, cluster 4 exhibited higher elbow angular velocity during extension (i.e., recovery) ($F(3,10) = 4.78, p = .026, \eta_P^2 = .590, p_s < .048$ for post hoc), but lower amplitude of elbow movement ($F(3,10) = 5.08, p = .022, \eta_P^2 = .603, p = .016$ for post hoc) as observed from the lowest maximal value reached during complete extension ($F(3,10) = 3.96, p = .042, \eta_P^2 = .543, p = .031$ for post hoc). In addition, different values of elbow angle at beginning of the cycle were revealed ($F(3,10) = 9.51, p = .003, \eta_P^2 = .741$), validating the previous results observed from the CRP value at the beginning of the cycle. Namely, cluster 3 showed a lower value of elbow angle at the beginning of the cycle ($p_s < .019$) while cluster 4 showed higher value ($p_s < .033$), which resulted in more streamlined arms during the beginning of

the cycle (i.e. during legs extension). Finally, cluster 1 exhibited a higher elbow angular velocity ($F(3,10) = 4.45, p = .031, \eta_p^2 = .572$) compared to cluster 2 ($p = 0.027$).

As previously highlighted in coordination profiling, when performing in highly constrained environment, individuals exhibited less possibilities to vary their behaviour. In this condition, individuals with cluster 1 movement pattern primarily exhibited a lower value of elbow angle at the beginning of the cycle ($F(1,12) = 29.48, p < .001, \eta_p^2 = .711$), which could be accounted for by the lower value of elbow angular velocity during extension ($F(1,12) = 12.77, p = .004, \eta_p^2 = .516$). Indeed, this lower value of angular velocity during extension could be the reason for the lag in reaching the maximal elbow extension.

Table 3. Mean and SD of movement pattern variables as a function of cluster and level of environmental constraints.

Outcome Variables	Highly Constrained Environment				Weakly Constrained Environment							
	Cluster 1		Cluster 2		Cluster 1		Cluster 2		Cluster 3		Cluster 4	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Elbow at beginning (°)	100.57	13.42 *	143.06	15.78	114.46	19.23	101.48	11.41	67.84 ^a	8.22	136.83 ^{b,c}	14.80
Elbow angle amplitude (°)	103.05	13.27	107.56	10.42	113.76	6.96	96.33	12.85	97.46	6.70	85.86 ^a	6.27
Maximal Elbow angle (°)	160.93	6.14	163.96	6.45	164.17	7.44	167.22	7.57	161.06	3.84	150.52 ^b	5.20
Maximal Knee angle (°)	171.24	2.97	172.25	4.55	170.11	4.29	173.22	3.10	168.88	6.64	173.69	2.05
Knee angle amplitude (°)	133.16	5.23	129.40	5.01	127.15	4.90	130.89	6.11	127.70	11.72	130.38	8.24
Knee angular velocity during f	-331.75	72.72	-373.79	44.41	-212.93	28.89	-222.54	41.55	-219.49	30.14	-220.63	29.77
Knee angular velocity during e	701.63	58.43	719.47	89.27	503.12	40.87	494.85	36.74	601.05 ^{a,b}	3.44	674.45 ^{a,b}	38.60
Elbow angular velocity during	342.45	53.10 *	505.67	108.52	257.70	85.27	227.65	59.44	210.99	26.77	376.39 ^{b,c}	86.32
Elbow angular velocity during	-370.95	75.01	-408.70	35.59	-367.70	33.03	-277.71 ^a	47.02	-292.70	24.90	-293.33	32.91

Note. In weakly constrained environment: a = significantly different from Cluster 1; b = significantly different from Cluster 2; c = significantly different from Cluster 3. In highly constrained environment: * = significantly different from Cluster 2; for all $p < 0.05$

Movement Patterns

In addition to coordination profiling, Figure 4 and Table 1 present the characteristics of each oscillator. In the weakly constrained condition, the differences between clusters appeared mainly on the elbow rather than on the knee. Indeed, individuals exhibited a similar knee pattern in both weakly and highly constrained conditions. The only exception is the presence of a higher knee angular velocity during extension (i.e., propulsion) for clusters 3 and 4 in a weakly constrained environment ($F(3,10) = 18.81, p = .001, \eta_p^2 = .849, p_s < .048$ for post hoc) (Table 1).

Conversely, clusters are differentiated by the movement pattern of the elbow that appeared as a key factor of the coordination. More precisely, in weakly constrained environment, cluster 4 exhibited higher elbow angular velocity during extension (i.e., recovery) ($F(3,10) = 4.78, p = .026, \eta_p^2 = .590, p_s < .048$ for post hoc), but lower amplitude of elbow movement ($F(3,10) = 5.08, p = .022, \eta_p^2 = .603, p = .016$ for post hoc) as observed from the lowest maximal value reached during complete extension ($F(3,10) = 3.96, p = .042, \eta_p^2 = .543, p = .031$ for post hoc). In addition, different values of elbow angle at beginning of the cycle were revealed ($F(3,10) = 9.51, p = .003, \eta_p^2 = .741$), validating the previous results observed from the CRP value at the beginning of the cycle. Namely, cluster 3 showed a lower value of elbow angle at the beginning of the cycle ($p_s < .019$) while cluster 4 showed higher value ($p_s < .033$), which resulted in more streamlined arms during the beginning of the cycle (i.e. during legs extension). Finally, cluster 1 exhibited a higher elbow angular velocity ($F(3,10) = 4.45, p = .031, \eta_p^2 = .572$) compared to cluster 2 ($p = 0.027$).

As previously highlighted in coordination profiling, when performing in highly constrained environment, individuals exhibited less possibilities to vary their behaviour. In this condition, individuals with cluster 1 movement pattern primarily exhibited a lower value of elbow angle at the beginning of the cycle ($F(1,12) = 29.48, p < .001, \eta_p^2 = .711$), which could be accounted for by the lower value of elbow angular velocity during extension ($F(1,12) = 12.77, p = .004, \eta_p^2 = .516$). Indeed, this lower value of angular velocity during extension could be the reason for the lag in reaching the maximal elbow extension.

Table 4. Mean and SD of movement outcome variables as a function of cluster and level of environmental constraints.

Variables	Highly Constrained Environment				Weakly Constrained Environment							
	Cluster 1		Cluster 2		Cluster 1		Cluster 2		Cluster 3		Cluster 4	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Stroke Rate (Hz)	0.72	0.11	0.73	0.15	0.36	0.06	0.34	0.06	0.33	0.02	0.29	0.04
Swimming speed (m)	0.96	0.08	1.02	0.11	0.62	0.06	0.59	0.04	0.64	0.09	0.68	0.08
Maximum Acceleration during legs	2.54	0.71	2.18	0.71	1.13	0.48	1.19	0.22	1.59	0.26	1.55	0.41
Maximum Acceleration during arms	1.39	1.01	1.41	0.78	0.40	0.26	0.41	0.21	0.71	0.22	0.98 ^{a,b}	0.23
Distance covered during legs propu	44.42	12.31	47.91	13.15	0.43	0.07	0.40	0.03	0.45	0.12	0.40	0.07
Distance covered during arms propu	26.86	19.57	32.77	17.47	0.23	0.06	0.26	0.08	0.47	0.12	0.51	0.14

Note. In weakly constrained environment: a = significantly different from Cluster 1; b =significantly different from Cluster 2; for all p < 0.05

Performance Outcomes

The study of performance outcomes resulting from the adopted coordination pattern revealed that in both weakly and highly constrained environments, the different clusters of movement demonstrated the same mean swimming speed (Table 4). Similarly, no differences were revealed in terms of stroke rate.

Movement Effect

Finally, despite the clusters showing different coordination patterns in weakly constrained environment, only cluster 4 showed a higher peak for acceleration of the CM during arm propulsion as compared to clusters 1 and 2 ($F(3,10) = 5.11, p = .021, \eta_p^2 = .605$, all $p_s < .031$ for post-hoc) (Table 4). It should be noted that this higher peak of acceleration did not lead to higher distance covered during arm propulsion. For all the variables relating to the leg propulsion phase (i.e., acceleration peak of the CM and distance covered by the CM), no differences were found. In highly constrained environment, no differences were found for movement effects. Indeed, for both acceleration of the CM during leg propulsion and arm propulsion, and for the distance covered by the CM during these two phases, cluster 1 and cluster 2 exhibited no significant differences.

Discussion

The aim of this study was to examine degeneracy in coordination modes in relation to movement effects (i.e., acceleration peak and distances covered by CM during propulsive phases) and performance outcomes (i.e., swimming speed and stroke rate) in a task with an emphasis on movement form. Instead of traditional

cohort studies, which focus on expert-novices comparisons, we investigated coordination variability for participants who are actually in the process of acquiring a functional coordination (i.e., between coordination and control stage of learning).

System's degeneracy regarding task realization, performance and movement effects

Based on previous work in both discrete and cyclic multi-articular actions (e.g., Hong & Newell, 2006a; Pinder et al., 2012; Rein, et al., 2010b), the present findings revealed evidence of system degeneracy (Edelman & Gally, 2001), with cluster analysis performed on coordination data highlighting the existence of different motor organizations for an identical task. In both highly and weakly constrained environment, participants showed two and four different patterns of coordination respectively. In addition to previous studies where the outcome in the task was binary, namely “realized” or “not realized” (e.g. Hong & Newell, 2006a), we tried to go further in the definition of “same function or same output” (Edelman & Gally, 2001, p. 13763) by measuring task performance. In this idea, neurobiological degeneracy was obvious as no difference in terms of performance in the task was revealed between groups (e.g. speed of task realization). In the same idea, results showed that different patterns led to the same movement effects (i.e., acceleration and displacement of the CM). Only an exception occurred under the weakly constrained environment where cluster 4 exhibited a higher peak of acceleration of the CM during arm flexion (i.e., arms propulsion), but the distance covered by the CM captured within this cluster during arms flexion did not appear significantly higher. It should also be noted that cluster 4 exhibited the coordination pattern closest to that seen in the expert pattern (Seifert et al., 2011). However, the absence of higher performance outcome observed in participants demonstrating this pattern is indicative that they have not yet moved beyond the control stage of learning. Overall, results highlighted that individuals can use different coordination not only while performing the same task (i.e. breaststroke swimming), but also while performing this task at the same speed and with identical movement effects.

System's degeneracy supporting motor exploration

Even in highly constraining activities like swimming, where the use of a specific effective pattern is assumed to be critical in achieving performance expertise, the neurobiological system's degeneracy may be highly functional in offering the flexibility to develop the required individualised coordination patterns (Seifert et al., 2013). Therefore, for learners seeking to develop a functional coordination, system's

degeneracy highlighted in this experiment could support the functional role of movement variability while allowing motor exploration during learning. The increase in motor variability early during learning has been highlighted by Vereijken et al. (1992) on learning a ski simulator task. Specifically, these authors showed that learners go through a preliminary phase of freeing the degrees of freedom so that the to-be-learned coordination can settle and stabilize (from coordination to control stage), thereby allowing an improved performance in increasing the amplitude of movement on the ski platform (and therefore eventually moving beyond the control stage of learning to the skill stage). Vereijken et al. (1992) therefore showed a non-linear relationship between coordination and performance outcome that may highlight the critical role of degeneracy during learning. Indeed, in the present study, even when participants navigating between coordination and control stage of learning exhibited the same performance outcome, the different profiles of coordination were associated with different higher order derivatives supporting performance. Particularly, the different emerging clusters differed in knee angular velocity during extension (i.e., propulsion) and elbow angular velocity during extension and flexion (i.e., propulsion and recovery). Therefore, the different patterns of coordination exhibited by swimmers may be due to the variation in *how they explore movement patterns* by manipulating higher order derivatives like angular velocities or angular amplitude. As highlighted by Chow et al. (2007) in a soccer kicking study, novice participants did not show the ability to vary higher order derivatives like foot velocity at ball contact as compared to skilled participants. Clearly, neurobiological degeneracy plays a paramount role in defining *explorative learning*, by allowing performers (especially between coordination and control stage of learning) to explore and discover functional relationships between manipulating higher order derivatives and meeting the specific task demands.

Interestingly at the level of individual oscillators, results showed that only one oscillator primarily offered the potential for exploration. Indeed, results showed that differences in inter-limb coordination were mostly due to differences in elbow patterns, rather than in knee patterns. This result is in line with previous results on four-limb coordination from Kelso & Jeka (1992), which reported how the arms are most likely to influence the overall coordination in four-limb movements. Kelso & Jeka (1992) highlighted that the transition from anti-phase to in-phase mode resides mainly in a “down” transition, namely a transition exhibited by the arms gaining a half cycle of movement to the leg (i.e., instead of an “up” transition in which leg

moves faster than the arm for one or a few cycles in order to gain a cycle) (Kelso & Jeka, 1992). This phenomenon principally occurred at oscillation frequency higher than 1.75 Hz in Kelso's work, which is higher than the present frequency of elbow and knee oscillations (i.e., around 0.35 and 0.75 Hz).

System's degeneracy impacted by the level of interacting constraints

Interestingly, this difference in oscillation frequency may reflect the constraining nature of the environment in breaststroke swimming, and presents a strong case to highlight the role played by the interacting constraints acting on participant's behaviour in this swimming task (i.e., interaction of task, environmental and organismic constraints, Newell, 1986). Particularly, the high level of environmental constraint in aquatic locomotion may interact with the task constraint (i.e., frequency of oscillation) which can account for the increase predominance of "down" transitions. More generally when the different swimming conditions were compared (i.e., highly and weakly constrained environment), the number of emerging clusters appeared lower when the constraints were higher (two clusters in highly constrained environment and four clusters in weakly constrained environment respectively). One of the main explanations of this result might be the higher level of forward resistance a swimmer has to face when the speed is increased. Indeed, Kolmogorov et al. (1997) have shown specifically in breaststroke that forward resistance goes from 20 N when speed is 0.9 m.s^{-1} to 90 N when the speed is 1.5 m.s^{-1} .

This result is congruent with the idea of interacting constraints that channel emergent coordination, suggesting that the potential variations of coordination pattern can be altered by the level of constraints acting on performers (Newell, 1986). In paradigmatic works on bimanual coordination (see Kelso, 1995), it has already been shown that the level of task constraint (frequency of finger-oscillations) can limit the possible number of emerging coordination pattern (i.e., from multi-stability to mono-stability). As suggested by Hong & Newell (2006b), a large number of degrees of freedom offers the potential for degeneracy to surface. However, the present study also showed that the variation in the level of interacting constraints also plays an important role in offering the potential for degeneracy.

System's degeneracy supporting the potential for motor re-organization

The results from the present study highlighted the pluripotentiality of dynamical degrees of freedom that degeneracy offers to neurobiological systems. Indeed, results showed that cluster one in a weakly constrained environment significantly different to the other clusters in terms of amplitude of elbow angle,

validating that altering the involvement of mechanical degrees of freedom is one mechanism for degeneracy to surface (Hong & Newell, 2006b; Vereijken et al., 1992). In addition, the absence of different involvement of mechanical degrees of freedom for the other clusters in both highly and weakly constrained environment suggests that interacting constraints affect not only these degrees of freedom, but also the spatiotemporal organisation of these mechanical degrees of freedom (Hong & Newell, 2006a).

The present study also showed that a possible channel for degeneracy to emerge reside in the pathway in which the same elements (i.e., biomechanical degrees of freedom) of neurobiological systems can be organised in different ways. This observation is reflected by the non-linear correspondence between clusters in weakly constrained environment to highly constrained environment. More precisely, the use of one pattern in weakly constrained environment did not necessarily define the nature of the pattern used in highly constrained environment and vice versa. Indeed, as shown in Figure 28, each cluster in one environmental condition includes participants from each of the clusters present in the other environmental condition. Therefore, in a given situation, diverse sets of components can be recruited and organized to achieve the same function (i.e., many-to-one mapping) (Whitacre, 2010), but a set of components can also be recruited and organized differently in order to functionally respond to interacting constraints (i.e., one-to-many mapping). By offering the potential for the involvement of additional mechanical degrees of freedom, as well as the potential for non-linear reorganization of dynamical degrees of freedom, degeneracy therefore offers opportunities for later exaptations and learning.

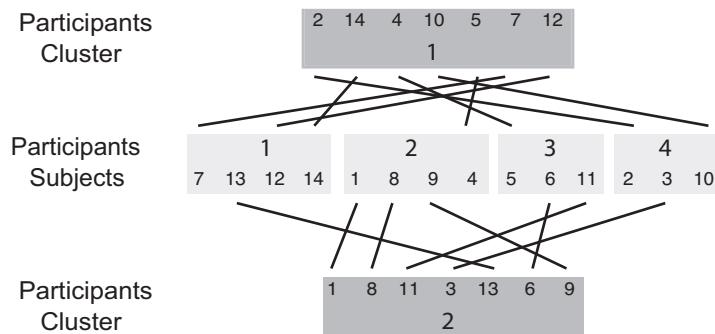


Figure 28. Correspondence between clusters' participants in highly constrained environment (dark grey) and weakly constrained environment (grey).

Conclusion

The previous discussed results support the following conclusion: i) even in a highly constrained activity where an assumed specific pattern is required to acquire expertise, degeneracy is omni-present as evident by the different patterns of coordination exhibited by learners who are seeking to develop a functional movement pattern (i.e., between coordination and control stage of learning); ii) this degenerate behavior seemed mostly reflected by variability of one oscillator, namely the elbow which seems to direct the non-homologous limb coordination; iii) emerging clusters differed in terms of higher order derivatives like elbow and knee rotation speed, and the degenerate behavior may help to define *explorative learning*, as the exploration of the relationship between these higher order derivatives and interacting constraints; iv) degeneracy allows both the stability of a function through a many-to-one mapping, but also a potential novelty through a one-to-many mapping such that a set of components can be reorganized differently (with possible additional involvement of degrees of freedom). Therefore, in motor skill acquisition, degeneracy can have a functional role in both ensuring stability as well as flexibility of a to-be-learned coordination pattern so that learners can be encouraged to explore the key relations between higher order derivatives and interacting constraints.

Chapter 5: Effect of analogy instructions with an internal focus on learning a complex motor skill

This chapter is based on the following article:

Komar, J., Chow, J.-Y., Chollet, D, Seifert, L. (in press) Effect of analogy instructions with an internal focus on learning a complex motor skill. *Journal of Applied Sport Psychology*.

A basic understanding of motor learning theory provides a support for practitioners and guides them in the design of effective skill instructions and suitable practice environments. By adopting an ecological dynamics perspective on human movement (Araujo, Davids, & Hristovski, 2006), researchers can better comprehend how a variety of goal-directed behaviours surface across individuals under similar constraints. The question of how humans generate accurate and adaptive (i.e. both stable and flexible) behavioural patterns particularly points towards two constituent issues; namely, the coordination of the neuro-musculoskeletal components of the body and the appropriate adaptation of these behavioural patterns to the environment (Warren, 2006). Nicolaï Bernstein (1967) first proposed that motor behaviour in complex neurobiological systems is achieved through managing redundant degrees of freedom (DoFs) into a coordinative structure (known as Bernstein's degrees of freedom problem). For instance, while learning to kick a ball, drive a car, or ski (Chow, Davids & Button, 2007; Vereijken, van Emmerik, Whiting & Newell, 1992), it is easier to regulate small subsets of coordinated DoFs than all individual DoFs of the body independently. The reduction of large numbers of DoFs into coordinative structures has been characterised as emerging from the interaction of constraints, which reduces the set of possible solutions to a single and adaptive motor solution. The establishment and development of such coordinative structures is an important process in skill acquisition and is highly dependent on the specific constraints in the learning context.

Verbal Instructions as Constraints to Enhance Motor Skill Acquisition

As highlighted by Davids et al. (2008), the constraints-led approach provides a fruitful framework for understanding the use and effect of verbal instructions as constraints on movement. *Nonlinear pedagogy* is based on the principles of ecological dynamics (Chow, Davids, Button & Shuttleworth, 2007) and highlights the critical

role of verbal instructions in learning. A paramount point is that the result of the learning process is deeply individual behaviour, adapted to the participant's own constraints (e.g. height, weight, cognitive capabilities) (Chow, Davids, Button & Koh, 2008). In nonlinear pedagogy, error-reduction towards a specific model is thus not relevant. The challenge for instructors is instead to create conditions that facilitate the exploratory process for the learner, rather than merely providing a precise description and prescription of the movement pattern (Chow, Davids, Button & Shuttleworth, 2007; Handford, Davids, Bennett & Button, 1997; Newell & Ranganathan, 2011).

Implicit Learning and Use of Analogy

If verbal instructions can be seen as global and covering a macroscopic variable of the movement (i.e. they represent one constraint that shapes behaviour), action rules and procedural knowledge need not be precisely explained to the learner and explorations of individualised movement solutions can instead be encouraged. In this sense, one of the major characteristics of the verbal instruction considered as a task constraint is its implicit valence to the detriment of the explicit one (Masters, 2000). Indeed, explicit emphasis on movement skills through precise verbal information may provide too much information and too narrow a focus for individual learners. According to Masters (1992), explicit instructions encourage learners to develop an overly high level of awareness of movement during practice, which can then be more easily perturbed by factors like anxiety, cognitive processing, fatigue or emotion. Conversely, the use of analogy is an alternative and practical method that elicits implicit learning and therefore a less conscious control of movement (Masters, 1992, 2000). Following a simple analogy or macroscopic instruction, learners can freely explore the workspace and unconsciously use the camouflaged rules needed to efficiently perform the task (Masters, 2000).

For instance, simple movement analogies delivered as verbal instructions have been shown to positively decrease the learner's processing load in learning table tennis topspin (Liao & Masters, 2001). Moreover, analogies can be considered as biomechanical metaphors that present information about the whole or global way to move in order to complete a task by repackaging the task-relevant rules, cues and knowledge into a single heuristic (Masters, 2000). For instance, 'glide like a torpedo' is an analogy in which a fundamental biomechanical principle of movement is made known without being explicitly stated (Seifert, Button & Brazier, 2011, p. 93). Other examples include asking table tennis learners to imagine a right-angled triangle and to swing the racket along the hypotenuse while hitting the ball (Liao & Masters, 2001),

or basketball learners to shoot the ball as if they were going to ‘put cookies in a cookie jar’ (Lam, Maxwell & Masters, 2009a; Lam, Maxwell & Masters, 2009b). In the same vein, Koedijker et al. (2011) used a culturally modified analogy (i.e. ‘move the bat as though it is travelling up the side of a mountain’, p. 251), as did Poolton et al. (2007), and showed that analogy instruction reduced the tendency to direct attention towards step-by-step execution. As suggested by the authors, the results indicated that the analogy group bypassed the declarative stage of learning (Koedijker et al., 2011).

Analogy Use and Focus of Attention

Interestingly, the use of analogy may correspond to some extent to the use of an internal focus of attention (i.e. attention is directed to the movement form) rather than an external focus (i.e. on the movement outcome) (see Peh, Chow & Davids, 2011, for a review). Internal focus was originally defined as being ‘where attention is directed to the action itself’ as opposed to an external focus ‘where the performer’s attention is directed to the effect of the action’ (Wulf, Lauterbach & Toole, 1999, p. 120). Even though the mechanisms underlying the effects of attention on learning are not clear, a considerable body of research has suggested that using an external focus of attention in instructions can help athletes reach higher performance (Wulf et al., 1999; Wulf, Shea & Park, 2001; Wulf, McConnel, Gärtner & Schwarz, 2002; Wulf & Weigelt, 1997). For instance, during golf swing learning, focusing on the motion of the club appears more beneficial than focusing on the swinging motion of the arms (Wulf et al., 1999). Nevertheless, although the external focus of attention has generally been shown to be more effective, some authors have pointed out that an internal focus of attention with respect to the acquisition of movement coordination can still be effective (Peh et al., 2011). The main debate centres on the relationship between the optimal focus and the performance level, with the assumption of some being that novices are more likely to benefit from an internal focus of attention (Peh et al., 2011; Uehara, Button & Davids, 2008). Yet few studies have shown that directing learners towards an internal focus would be as beneficial as towards an external focus (Uehara et al., 2008; Zentgraf & Munzert, 2009). In Uehara’s study, the task was to chip a stationary soccer ball, and there were several internal instructions concerned with each phase of the chipping action (Uehara et al., 2008). Similarly, in the study of Wulf et al. (1999) on golf swing learning, the swinging motion of the arm was defined by the precise position of both arms and during each phase of the movement.

Little attention has been given to analogy and its relevance to internal focus of attention instructions. Some researchers have suggested that analogy use can have a positive effect by directing attention to movement mechanics without explicitly trying to control the movement (Lohse & Sherwood, 2011). Thus, if an analogy is used but is less prescriptive, perhaps there are potential benefits for skill acquisition even though it still emphasizes aspects of movement form. This kind of analogy could provide insight into how the use of analogy coupled with an emphasis on coordination can provide learners with an approximation of the biomechanically desirable movement forms that will reduce unnecessary and less meaningful searches in the learning context. In this context, the verbal instruction is no longer overly prescriptive and does not contribute to reinforcing a general model for goal-directed action. Instead, it is viewed as regulating the movement and as providing a boundary for exploring possibilities. It would be interesting to determine whether the use of this type of analogy, which can be seen as a microscopic input, would eventually lead to a qualitative change in macroscopic output, providing evidence for the use of a nonlinear pedagogical approach.

In the present study, we sought to put into practice key concepts of ecological dynamics, thereby bridging the gap between learning theory and practice. We assessed the benefits of using a verbal instruction to subjects learning a new behaviour in a goal-directed task. This verbal instruction emphasised an internal focus delivered as an analogy. The measurement of both quantitative improvement (i.e. in terms of performance) and qualitative changes (i.e. in terms of an emerging new behaviour) induced by the analogy instruction is pertinent to understanding the impact of different types of verbal instruction. A multi-articular task like breaststroke swimming is a suitable movement task, as the movement form is critical but not unique and predetermined. Moreover, it allows the assessment of coordination changes, as well as performance efficiency (Seifert, Leblanc, Chollet, & Delignières, 2010).

First, we predicted that the group receiving information about the general goal of the learning task and the movement form (i.e. through an analogy) would show a significant reorganisation in inter-limb coordination. More precisely, this analogy group was expected to exhibit both a glide phase and the dissociation of the propulsive and recovery phases during the cycle. Second, we hypothesised that these changes in motor organisation would lead to significant improvement in swimming performance for this group (i.e. an increase in stroke length for a given speed).

Method

Participants

Students from the Sports Department of the university, all novices in breaststroke, voluntarily participated in this study ($N = 12$). Each participant signed an informed consent form after receiving oral and written descriptions of the procedure, which was approved by the university ethics committee. The participants were separated into 2 groups of 6 participants each and they were randomly assigned to the analogy group or the control group. The analogy group was composed of 3 women and 3 men aged between 20 and 22 years ($M = 20.3$ years, $SD = 0.9$). Their mean height was 1.71 m ($SD = 0.13$), their mean weight was 60.8 kg ($SD = 6.5$), their mean number of hours of physical activity per week was 14.5 hours ($SD = 1.9$), and their average speed over 25 m in breaststroke at maximal effort was 1.04 m.s^{-1} ($SD = 0.11$). A control group was composed of 2 women and 4 men aged between 20 and 23 years ($M = 20.8$ years, $SD = 1.2$). Their mean height was 1.74 m ($SD = 0.12$), their mean weight was 66.3 kg ($SD = 8.8$), their mean number of hours of physical activity in a week was 14.0 hours ($SD = 2.8$), and their average speed over 25 m in breaststroke at maximal effort was 1.03 m.s^{-1} ($SD = 0.10$).

All the participants had learned only the basics of breaststroke swimming during high school (i.e. 2 courses of 10 lessons each during high school) and had never been engaged in breaststroke swimming elsewhere (e.g. clubs). Two swimming instructors selected the 12 individuals from a pool of approximately 150 swimmers who performed a 50-m breaststroke swim at a comfortable speed. The two exclusion criteria were principally related to the validity of their initial breaststroke technique: they had to be able to (a) perform a symmetrical leg kick and (b) perform leg and arm movements at the same frequency. The swimming instructors characterized the swimmers as being in the first stage of learning (i.e. coordination stage), during which learners still have to establish the basic relationships among the key components of the behaviour (Newell, 1986). The main characteristics of swimmers at this stage are a lack of glide between cycles, mainly because of uniform motions (i.e. no limb acceleration during propulsion and no glide time) and a superposition of contradictory actions (e.g. leg propulsion during arm recovery) (Seifert, Leblanc et al., 2011; Seifert et al., 2010).

Learning Design

All participants had to complete 18 sessions of practice and three test sessions (pre-test, post-test and retention-test). All practice sessions were completed within ten weeks at a frequency of two sessions per week (Wednesday and Friday). Participants were required to perform the swimming task in a 25-m indoor pool and performed 10×25 m at moderate velocity (i.e. 70% of their maximal speed). Each session lasted 60 minutes in the swimming pool and consisted of a 10-minute warm-up followed by the ten laps with a departure every 4 minutes (i.e. each swim consisted of a 30-sec swim and 3 min 30 sec of rest). This moderate speed, based on the maximal speed achievable by the participant (performed 1 week before the beginning of the protocol), corresponded to the working speed used during the entire learning process. The learning sessions for each group took place at different times to ensure that the two groups did not have any knowledge about the intervention conditions of the other group. To assess the learning process, three tests were conducted and analysed, a pre-test during the first lesson, a post-test during the last session (i.e. 20th lesson) and a retention test two months after the post-test. Participants were informed that they should not undertake any other practice beyond the learning sessions during the experimental period.

General Goal of Learning and Specific Instruction

The general goal of the swimming task was to increase the stroke length through a self-paced stable speed for the two groups of participants. The swimmers were informed of this goal and the rules of breaststroke swimming were reviewed in the first lesson and thereafter only if necessary. The two rules were: (a) hands cannot go behind a vertical line passing through the shoulders and (b) a cycle always consists of one arm and one leg movement. When swimmers broke one of these rules, the swim was cancelled and done again.

No other information was given to the control group during the entire study. The analogy group was informed about the goal of the task and the same breaststroke rules, plus an additional instruction was given focusing on a single microscopic variable of the cycle: ‘glide 2 seconds with your arms outstretched’. Indeed, according to ecological dynamics theory, one set of limbs is considered as leading the other one during the cycle (Faugloire, Bardy & Stoffregen, 2009). Therefore, in breaststroke swimming, the arms lead the entire coordination, and giving instructions only on the arms could cause a global reorganisation of arm-leg coordination.

As the instruction focused specifically on the glide position of the arms, this additional information was deemed relevant as an analogy that provided a biomechanical metaphor regarding the hydrodynamic outstretched position. Thus, the participants did not need to stop with their arms outstretched for 2 seconds, but to seek and maintain this gliding position. This analogy instruction therefore informed about a hydrodynamic characteristic of the movement but did not explicitly specify either the exact movement (e.g. individuals could use a pronated and superposed position of the palms, palms facing out, or palms pronated side by side) or the exact coordination pattern to adopt. This point is paramount because, by encouraging the outstretched arm position for gliding, the analogy also encouraged the macroscopic reorganisation of the entire coordination. Indeed, the glide phase of the arms not only serves the general glide of the full body, but also prepares a hydrodynamic profile for leg propulsion. From this perspective, the original analogy of ‘gliding like a torpedo’ was considered as too restrictive in terms of the to-be-learned coordination, by imposing the position of both arms and legs and by focusing only on the glide phase of the entire body.

Moreover, as noted by Liao and Masters (2001, p. 308), an analogy is a ‘verbal representation of the task to be executed (...) relying very little on explicit verbal instructions or rules’. Instead of giving a set of explicit verbal instructions related to the body movements during all the cycle phases (e.g. Wulf, Lauterbach, & Toole, 1999, p. 122), the experimental instruction was only directed at the specific gliding position of the arms, considered as an internal focus of attention (in line with Wulf et al. [1999, p. 121], who directed focus ‘at the swinging motion of the arms’ in golf), without imposing anything in terms of arm-leg coordination. The instruction was unique and did not cover all of the different phases of the breaststroke cycle (i.e. leg propulsion, glide, arm propulsion, or arm and leg recovery); moreover, it did not focus on each specific phase.

Motor Outcomes

One underwater (0.5 m) side-view camera (Panasonic NV-GS17, 50 Hz) was mounted on a trolley running along the right side of the pool. An experimenter operated the camera system by ensuring that the position of the camera was positioned orthogonally to the hip of the swimmers while the trolley was being pushed. During each test, one complete swim (i.e. 25 m) was recorded on video for each participant. White body markers were placed on the anatomical landmarks of the wrist, elbow, shoulder, hip, knee and ankle on both sides of the swimmers. For each

swim, ten cycles were then digitised, and the time was normalised and averaged (each cycle begins at a maximal knee flexion and ends at the next maximal knee flexion). The mean speed (v in m.s^{-1}) and mean stroke rate (SR in Hz) were assessed for each swim. Task performance and changes in coordination with learning (i.e. stroke length [SL] in m.cycle^{-1}) were assessed for each swim based on the mean speed and the mean SR following the equation $SL = v \times SR$. The product of swimming speed and stroke length was calculated as a stroke index (SI), which is a global indicator of swim efficiency (Costill et al., 1985).

Digitalisation of body markers on the video data allowed 2-D reconstruction of elbow and knee angles using Simi Motion software (Simi Reality Motion Systems GmbH, Germany). Based on previous work by Haken, Kelso, and Bunz (1985) on hand movements, arm-leg coordination was assessed using continuous relative phase (CRP) between two oscillators (i.e. elbow and knee angles). In accordance with Hamill, Haddad, and McDermott (2000), angular velocity was calculated and both angular position and velocity were normalised between -1 and 1 to calculate the CRP. Knee and elbow angles were first filtered using a low-pass Fourier filter (cut-off frequency 6 Hz). Phase angles were calculated for both elbow and knee using the following formula: $\phi = \arctan(\omega_{\text{norm}} / \theta_{\text{norm}})$, where ϕ is the phase angle in degree, ω_{norm} is the normalised angular velocity, and θ_{norm} the normalised angular position. Last, the CRP for a complete cycle was established following the equation $CRP = \phi_{\text{elbow}} - \phi_{\text{knee}}$. Theoretically, two extreme modes of coordination are possible: (a) in-phase ($CRP = 0^\circ$) and (b) anti-phase ($CRP = 180^\circ$). However, following previous studies on inter-limb coordination, a lag of $\pm 30^\circ$ was accepted to define the adopted coordination mode (Diedrich & Warren, 1998; Seifert, Delignieres, Boulesteix & Chollet, 2007). Therefore, an in-phase mode was assumed to occur when the CRP value was contained between -30° and $+30^\circ$, while an anti-phase mode was taken to be between -180° and -150° and between 150° and 180° . Based on CRP analysis, the CRP value at the beginning of the cycle provides information about the capability of the swimmers to synchronise the start of leg extension to the end of arm recovery. The time spent in-phase subtracted from the time spent with arms and legs outstretched represents how the swimmers superposed contradictory actions (i.e. leg propulsion with arm recovery or leg recovery with arm propulsion). The maximal peak of CRP indicates the period when the legs lead the arms in flexion or extension.

The quantity of inter-subject variability was assessed by the between-participants SD as a percentage of the entire cycle.

Data Analysis

Three types of dependent variables were analysed: (a) respect of the learning condition (i.e. swimming speed, percentage of error regarding the targeted speed, and time with arms outstretched), (b) the swimming parameters (i.e. SR, SL and SI), and (c) the coordination variables (i.e. time with legs outstretched, time with arms and legs outstretched, time spent in-phase, CRP at beginning, maximal CRP peak and intra-individual CRP variability). Prior to any analysis, normal distribution (Ryan Joiner test) and homogeneity of variance (Bartlett test) were verified. Two-way ANOVA for repeated measures (test session: within-participant factor [pre-test, post-test, re-test] \times group: between-participant factor [analogy, control]) determined the differences between the sets and groups. Moreover, pairwise comparisons between test sessions were conducted using a post-hoc test with Tukey's Honestly Significant Difference. To investigate the effect of the instruction on learning, the protocol was reduced to assess more precisely the effect of time of testing when an interaction of effect was revealed. When necessary, the p values were corrected for possible deviation from sphericity using the Greenhouse-Geisser epsilon (ϵ). For each significant effect ($p < .05$), we estimated effect size using partial eta squared η_p^2 (Cohen, 1988). Student's paired-sample t -test was used to analyse differences between the means of between-participants SD .

Results

Aspects of Learning Condition

Repeated measures ANOVA revealed the absence of significant differences in swimming speed between the test sessions, $F(1.26,12.57) = 0.142, p = .769, \eta_p^2 = .014, \epsilon = .628$, and between groups, $F(1,10) = .174, p = .686, \eta_p^2 = .02$ (Table 5). The percentage of error in the task was 2.83% ($SD = 2.24$) for the experimental group and 3.63% ($SD = 2.39$) for the control group. The stable swimming speed and low task error showed that participants were able to maintain the same targeted speed throughout the three test sessions.

Table 5. Performance variables during the three times of testing for both control

and analogy groups.

Variables	Experimental group						Control group					
	Pre-test		Post-test		Re-test		Pre-test		Post-test		Re-test	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Stroke Rate (Hz)	a,b	0.67	0.11	0.51	0.09	0.48	0.08	a,b	0.69	0.12	0.57	0.06
Stroke length (m)	a,b	1.20	0.18	1.55	0.37	1.62	0.35	a,b	1.14	0.26	1.39	0.20
Swimming speed (m/s)		0.79	0.08	0.79	0.10	0.78	0.07		0.79	0.07	0.78	0.06
Stroke Index (m^2/s)	a,b	0.96	0.17	1.28	0.43	1.33	0.37	a,b	0.88	0.25	1.19	0.26
											1.33	0.37

Note. a = significant differences between pre-test and post-test; b = significant differences between pre-test and re-test ; for all $p < .05$

A significant main effect of learning was revealed for the time spent with arms outstretched (Table 6), $F(2,20) = 8.47$, $p = .002$, $\eta_P^2 = .46$, but a main difference between groups also appeared, $F(1,10) = 20.16$, $p = .001$, $\eta_P^2 = .67$, as well as an interaction effect, $F(2,20) = 9.23$, $p = .001$, $\eta_P^2 = .48$. Subsequently, pairwise comparisons revealed that this increase in the time spent with arms outstretched appeared only for the analogy group ($ps < .001$). Significant differences between analogy and control groups therefore appeared at the end of learning ($ps < .006$), suggesting that the swimmers in the analogy group were able to adhere to the instruction.

Swimming Parameters

The mean and SD of swimming variables are detailed in Table 5. The results showed a significant decrease in SR during learning, $F(1.35,13.57) = 53.7$, $p < .001$, $\eta_P^2 = .83$, $\epsilon = .679$. SL increased, $F(2,20) = 28.13$, $p < .001$, $\eta_P^2 = .74$ and SI increased, $F(1.17,11.74) = 16.70$, $p = .001$, $\eta_P^2 = .62$, $\epsilon = .587$. Pairwise comparison for SR, SL and Si showed differences between pre-test and post-test ($ps < .001$) and a retention effect of learning ($ps < .040$). No significant differences were found between groups, nor were interactions observed (test session \times group), all $Fs(1,10) < 1.38$, $ps > .275$, $\eta_P^2 < .12$. These results showed that both groups were able to decrease their SR and exhibit greater distance covered per cycle, in order to maintain the swimming speed (i.e. as $v = SL \times SR$).

Coordination Variables

The mean coordination profiles for both groups are presented in Figure 29, and the mean and SD of coordination variables are detailed in Table 6. The results showed that after learning, both groups increased their time spent with legs outstretched, $F(1.43,14.32) = 71.66$, $p < .001$, $\eta_P^2 = .87$, $\epsilon = .587$. No difference

between groups was found in terms of time spent with legs outstretched, $F(1,10) = 1.27, p = .28, \eta_P^2 = .11$, and no test session \times group interaction was observed, $F(1.43,14.32) = 0.27, p = .697, \eta_P^2 = .03, \epsilon = .587$.

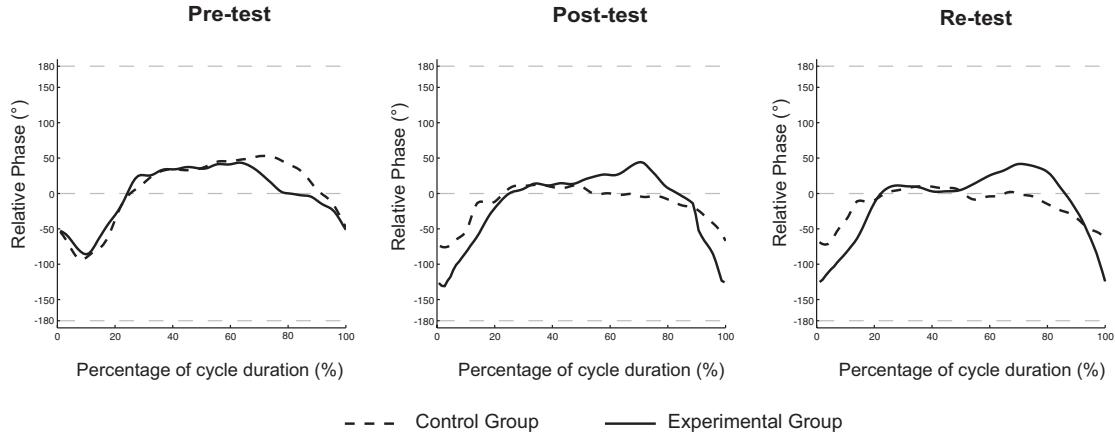


Figure 29. Mean patterns of continuous relative phase for the control group (dotted line) and the analogy group (continuous line) during the three times of testing.

Conversely, the analogy group spent more time gliding with both arms and legs outstretched than the control group, significant main effect of learning, $F(2,20) = 72.67, p < .001, \eta_P^2 = .88$, no difference between groups, $F(1,10) = 1.27, p = .29, \eta_P^2 = .11$, but a significant interaction, $F(2,20) = 26.53, p < .001, \eta_P^2 = .74$. Pairwise comparisons revealed an increase in gliding time with arms and legs outstretched for the two groups with learning ($p < .001$). But the analogy group exhibited a greater increase, as the time spent with arms and legs outstretched was significantly greater for this group at post and re-test ($p < .001$).

Table 6. Coordination variables for both control and analogy groups during the three times of testing.

Variables	Experimental group						Control group					
	Pre-test		Post-test		Re-test		Pre-test		Post-test		Re-test	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Time with legs outstretched (% of cycle duration)	a,b	9.5	11.6	42.5	9.0	43.5	12.2	a,b	6.8	12.9	35.4	5.8
Time with arms outstretched (% of cycle duration)	a,b,c	33.2	4.9	45.3	5.7	51.7	13.2	c	29.2	7.9	29.8	2.4
Time with arms and legs outstretched (% of cycle duration)	a,b,c	9.5	11.6	41.0	6.8	42.7	13.1	a,b,c	6.8	8.5	29.2	2.9
Time spent in Phase subtracting glide phase (% of cycle duration)	a,b,c	28.0	7.4	19.2	11.9	4.2	13.9	b,c	26.1	12.8	34.7	13.9
Relative Phase at begining (°)	a,b,c	-52.8	24.1	-123.6	21.8	-125.6	18.7	c	-51.6	28.9	-74.3	19.2
Maximal pic of Relative Phase (°)	c	56.6	26.8	47.1	39.9	49.5	45.8	a,b,c	73.9	30.1	9.8	38.8
											11.8	37.6

Note. a = significant differences between pre-test and post-test; b = significant differences between pre-test and re-test; c = significant differences between analogy group and control group at post-test and at re-test; for all $p < .05$

A decrease in in-phase time was correspondingly observed in the analogy group. Indeed, no main effect of learning was revealed, $F(2,20) = 0.197, p = .822, \eta_P^2 = .019$, but an test session \times group interaction was observed, $F(2,20) = 7.17, p = .004, \eta_P^2 = .418$. Post-hoc comparisons revealed a decrease in the time spent in-phase with learning ($ps < .031$). An increase in in-phase time occurred only between pre-test and re-test for the control group, whereas a difference between the analogy and control groups was found at post-test and re-test ($ps < .007$).

Figure 29 highlights the significant decrease in the CRP value at the beginning of the cycle with learning, only for the analogy group (a main effect of test session, $F(2,20) = 43.88, p < .001, \eta_P^2 = .81$, a main difference between groups, $F(1,10) = 9.456, p = .011, \eta_P^2 = .49$, and an interaction was also revealed, $F(2,20) = 10.45, p = .001, \eta_P^2 = .51$). Pairwise comparisons showed a significant decrease in the first value of CRP for the analogy group between pre-test and post-test ($p < .001$) and between pre-test and re-test ($p < .001$). No differences between tests were revealed for the control group in terms of this first value of CRP ($ps > .013$).

As seen in Figure 29, a significant main effect of learning was highlighted concerning the maximal peak of CRP, $F(2,20) = 8.54, p = .002, \eta_P^2 = .46$, but no significant difference between groups, $F(1,10) = 0.92, p = .359, \eta_P^2 = .08$. Nevertheless, a significant interaction effect was revealed for this maximal peak of CRP, $F(2,20) = 5.56, p = .012, \eta_P^2 = .36$. Subsequently, pairwise comparisons

revealed a decrease with learning in the maximal CRP value only for the control group ($p < .001$), whereas no differences between test sessions occurred for the analogy group ($p_s > .97$).

Last, no significant differences with learning were revealed in terms of intra-individual variability of the CRP, as the paired *t*-test computed on the between-participants *SD* of CRP (analogy group: $t = .60$, $p = .563$, and control group: $t = .759$, $p = .460$) showed no significant differences.

Discussion

This study sought to extend previous work on nonlinear pedagogy by putting ideas and concepts of ecological dynamics into practice. The qualitative changes in arm-leg coordination that occurred during learning showed the relevance of using analogy in learning the breaststroke. All participants increased their performance, but the analogy group did not show significant differences in performance compared with the control group. By using an analogy as an internal focus of attention, we highlighted the relevance of such an instructional constraint on improving coordination and the performance outcome (i.e. task goal of increasing stroke length) during learning.

Qualitative Changes in Coordination and Benefits of Using an Analogy

The present experiment showed the differences in qualitative changes during learning between a control and an analogy group, which were consistent with the findings of Lam et al. (2009a), who showed changes in behaviour while using an analogy in learning a basketball shooting task. More precisely, our results showed that the analogy instruction led to an increase in the time spent with arms outstretched for the analogy group, although both groups increased the time spent with legs outstretched. This longer period spent with arms outstretched was coupled with a decrease in the first value of CRP for the analogy group, indicating that this group was able to start leg propulsion with the arms already closer to maximal extension. As a consequence, these participants were able to minimise the superposition of contradictory actions (i.e. leg propulsion during arm recovery).

The analogy group also showed a longer time spent with arms and legs outstretched after learning, compared with the control group. The time spent in-phase subtracted from the glide time clearly showed the effectiveness of the analogy

condition in terms of limb coordination, as the irrelevant time spent in-phase increased for the control group while it decreased with learning for the analogy group. After learning, the propulsive actions occurred separately in relation to the recovery actions for the participants who received the analogy instruction. This result reveals that a single microscopic variable enabled the acquisition of a more efficient pattern (i.e. a long glide phase with arms and legs outstretched and a decrease in contradictory actions), while the partial superposition of actions remained for the control group.

The control group showed a decrease in the maximal peak of CRP, indicating that practice alone led to learning to delay the start of the leg recovery phase. This movement causes a decrease in resistance during the glide phase and arm propulsion. Unfortunately, this maximal peak remained high for the analogy group, as the arms were in a propulsive phase when the legs were recovering. The emergence of this coordination pattern may have been due to the effect of the verbal instructions to the analogy group participants, since they were asked to glide for 2 seconds with arms outstretched.

Although the 2-second requirement was only an indication of duration and not objectively counted, it may have encouraged the participants to maintain their arms outstretched for a longer time, therefore resulting in a movement pattern where the legs were in a recovery position while the arms were still outstretched, as seen during the pre-test. Interestingly, Seifert, Leblanc et al. (2011) showed in expert swimmers that the arms should already be in maximal flexion (i.e. completion of propulsion) when the legs are beginning to flex. The analogy used in the present study may have been too prescriptive compared with previous instructions like ‘glide like a torpedo’ or ‘glide like superman’ (Seifert, Button et al., 2011, p 93). Indeed, instead of using these analogies, which provided information on both arm and leg position, we sought to give only a single item of information for one set of limbs (i.e. arms). Our results support the suggestion that the arms have a leading role in coordination since the instruction in relation to the arms generated an improvement for the gliding position of both arms and legs. Adapting the analogy to a single item of information in order to manage coordination also seemed to be relevant, as the arm glide phase appeared to lead to more efficient arm-leg coordination by inserting a glide phase during leg propulsion. Nevertheless, imposing a time for outstretched position may have been too prescriptive since the impact of arm movement time could be task- and learner-dependent (e.g. dependent on swimming speed) (Chollet et al., 2004). Using the

analogy ‘glide like a torpedo with your arms’ would be an interesting alternative to avoid imposing a specific coordination and a specific timing for the movement. Such variation in responding to arm movement time, as an example, provides insight into the importance of respecting task dynamics when establishing a learning design (Pinder, Davids, Renshaw & Araújo, 2011).

Quantitative Changes in Performance with Learning

Despite the emergence of a more efficient pattern, however, no differences between groups in terms of performance or goal achievement (i.e. to increase stroke length) were observed. This unexpected result can be explained by different levels or types of non-expert behaviour (Seifert, Leblanc et al., 2011). Indeed, these authors showed that a group of swimmers with the same level of expertise can exhibit different but stable patterns of coordination to achieve the same task. In neurobiological systems, this principle is known as degeneracy and refers to the faculty of elements that are structurally different (i.e. different patterns of coordination) to perform the same function (i.e. the same task output) (Edelman & Gally, 2001).

In this study, the coordination pattern of the control group at post-test was closer to the pattern defined as the second level of breaststroke coordination (Seifert, Leblanc et al., 2011). At this early level of learning, these learners may have been preoccupied by forward propulsion for speed, but they were not yet capable of effective spatial and temporal organisation. They exhibited a time gap that was detrimental to going forward but still efficient for floating (Seifert, Leblanc et al., 2011). Conversely, the analogy group seemed to show evidence of acquiring a movement pattern that was more similar to that exhibited by most expert swimmers (i.e. biomechanically more efficient [Seifert, et al. 2010]). It seems that the participants exposed to the analogy condition adopted a pattern that can be described as the partial superposition of contradictory actions. This pattern has been defined as the most efficient among beginners’ patterns (Seifert, Leblanc et al., 2011). Therefore, the swimmers in the control group in this study seemed able to increase their stroke length by means other than a reorganisation of coordination. Delignières et al. (1998) found similar results during the early stages of learning to swing in gymnastics. In that case, performance improvement was due to an optimisation of the initial behaviour instead of the adoption of a more efficient pattern. For instance, the control group swimmers may have increased their force impulse during arm or leg propulsion in order to counteract the higher resistances due to their inefficient coordination.

Nevertheless, adopting an efficient pattern seems to be mandatory for acquiring expertise and reaching the highest stages of learning (Newell, 1986).

According to learning models that describe learning as comprising several stages, with each stage representing a different period in the learning process (i.e. coordination, control and skill [see Newell, 1986]), the participants were in a transition between being complete beginners and having some semblance to experts. From this perspective, all the participants were involved in a transition between the first stage (i.e. coordination) and the second one (i.e. control), searching for appropriate coordination between the limbs. Based on the suggestion from Chow et al. (2008) that coordination and control are often negotiated at the same time, we can therefore assume that both groups were navigating between these two stages (i.e. coordination and control).

Neither group displayed a stable coordination pattern, although there was some evidence that the movement pattern of the analogy group was more biomechanically efficient. The performance between groups may really differ only when they have attained the last stage (i.e. skill), as this stage is defined as skilled optimisation (Davids et al., 2008). According to Seifert, Leblanc et al. (2011), this may be the stage at which the participants would be able to properly deal with interacting constraints like aquatic resistance or Newton's third law (i.e. action-reaction) in order to move forward instead of being preoccupied by floating. This same phenomenon has been highlighted by Vereijken et al., (1992) on learning a ski simulator task. These authors showed that learners go through a preliminary phase of freeing the DoFs so that the to-be-learned coordination can settle and stabilise (from coordination to control stage), thereby allowing an improved performance in amplitude (from control to skill stage).

In this sense, the relationship between the qualitative changes in coordination and performance outcome may also be nonlinear, and the use of analogy in learning seems to be very interesting during these first stages of learning. Chow et al. (2006) argued that non-prescriptive practice is valuable at the coordination stage of learning to assemble a functional and unique pattern of coordination, and at the control stage to refine and adapt the basic coordination in order to interact with task and environmental constraints. Because it is less prescriptive, the use of analogy might allow learners to develop flexibility and therefore adapt to more varied environmental and task constraints. For instance, a characteristic of expert swimmers is their flexibility in qualitatively adapting their coordination to changing environmental

constraints like variations in aquatic resistance and swim speed, while beginners tend to remain in in-phase mode even when forward resistance increase with swim speed (Seifert et al., 2010; Seifert, Button, et al., 2011).

Analogy Learning and Internal Focus of Attention

The inter-participant variability did not show any improvement with practice. This finding indicates that the learners were able to develop personal patterns of coordination, even though they were guided towards a more efficient pattern: these swimmers changed their coordination without being locked into a stereotype by the instruction. As previously noted by Chow et al. (2006, 2011), the use of analogy allowed the development of desirable pattern solutions while preserving functional variability, whereas prescriptive pedagogy usually leads to the development of a single ideal pattern. The present study thus extends previous investigations on internal *vs.* external focus, which have consistently emphasised the beneficial effect of an external focus (McKay & Wulf, 2012; Wulf et al., 1999). The findings from this study suggest that an internal focus may also be useful in acquiring motor coordination, as long as it reflects a macroscopic variable of movement form (Peh et al., 2011).

Nonlinear pedagogy does not mean that educators should merely allow free play and let learners complete a task whatever way they think appropriate, but rather that educators have to facilitate new movement solutions by designing a learning environment that provides controlled boundaries for exploration (Brymer & Renshaw, 2010). This approach to design requires a respect for processes like task simplification rather than part-task decomposition, in the sense that learning designs have to preserve the complexity of the activity (Davids et al., 2008). Nonlinear pedagogy seems to provide a useful framework for dealing with both the stability of a to-be-learned pattern and the flexibility required by environmental, task and organismic constraints.

Limitations and Perspectives

Further investigations in this field are needed, mainly with regard to the limitations of the present study. Larger studies should be conducted because the low number of subjects in each of our groups likely weakened the value of the results. Also, comparison with an explicit learning group, accompanied by a transfer test, would further highlight the relevance of the instruction. Another direction for research would be to examine the impact of the exploratory activity undertaken by learners through the dynamic assessment of their behaviour.

Chapter 6: Temporal dynamics of learning: how informational constraints can impact exploratory behaviours during learning?

The general aim of this last experiment was specifically to investigate the nature of the exploratory strategies exhibited during learning breaststroke, through analysing the temporal dynamics of coordination acquisition. In addition, the impact of different additional constraints on the learning process has been investigated. More precisely, a first aim was to define in terms of motor coordination the nature of the transition that occurs with practice (e.g. abrupt or more gradual/continuous, including intermediate behaviors or periods of intermittency). The hypothesis was that the control group receiving only the general goal of learning as instruction should exhibit different patterns of coordination during the learning process, corresponding to an active exploration of the perceptual-motor workspace.

A second specific aim was to investigate the effect of different constraints on the exploratory strategies exhibited by learners. The use of instructions that were differently prescriptive was supposed to limit more or less the exploratory possibilities. The hypothesis was that a highly prescriptive instruction should provide strong boundaries to the exploration (or no exploration), whereas less prescriptive instructions should guide or limit the exploration without completely preventing it (Figure 30). It might exist a certain kind of constraints providing an optimal level of prescription to optimally guide the exploration, therefore showing an optimal ratio between exploration and exploitation.

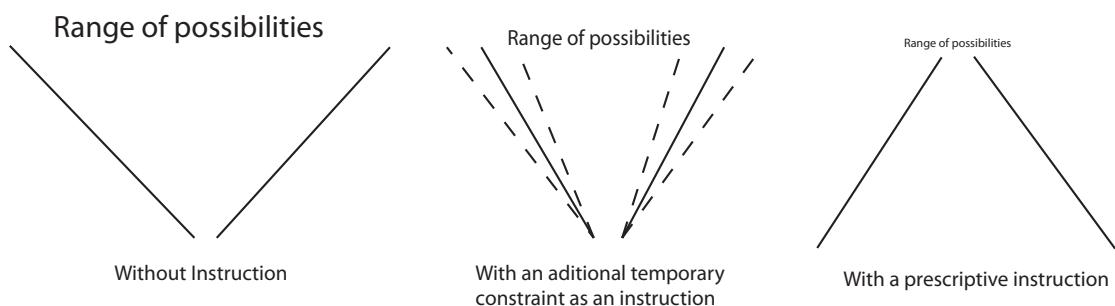


Figure 30. Range of possibilities in the exploration process without additional constraint (left), with an additional constraint (middle, the dotted line represent the effect of the nature more or less prescriptive of the additional constraint) and with a prescription of the to-be-learned pattern (right).

Last, a third specific aim was to investigate during the learning process the relationship existing between performance and exploratory behaviors. In other words, do the different strategies observed correspond to different profiles in the increase of performance? The hypothesis was that the exploration of the perceptual motor workspace allows to develop a stable and flexible pattern of coordination but could delay the increase in performance, and that these delays in performance increase could be associated to switching between patterns of coordination.

Method

Participants

Students from the Sport Sciences Department, all novices in breaststroke, voluntarily participated to this study ($N = 32$). Participants, all masculine, have been separated into four groups of eight participants each. The first group was called “control”, the second “analogy”, the third “pacer” and the last “prescription”.

The **control group** was composed by eight participants aged from 18 to 20 years ($M = 19.2$ years, $SD = 0.9$). Their mean height was 1.74 m ($SD = 0.76$), their mean weight was 63.1 kg ($SD = 4.5$) and their mean swimming speed during 25 m breaststroke at maximal intensity was 0.96 m.s^{-1} ($SD = 0.07$). The **analogy group** was composed by eight participants aged from 19 to 21 years ($M = 19.3$ ans, $SD = 0.5$). Their mean height was 1.79 m ($SD = 0.07$), their mean weight was 72.7 kg ($SD = 8.3$) and their mean swimming speed during 25 m breaststroke at maximal intensity was 0.99 m.s^{-1} ($SD = 0.05$). The **pacer group** was composed by eight participants aged from 19 to 22 years ($M = 20.0$ ans, $SD = 0.6$). Their mean height was 1.80 m ($SD = 0.09$), their mean weight was 73.0 kg ($SD = 9.8$) and their mean swimming speed during 25 m breaststroke at maximal intensity was 0.89 m.s^{-1} ($SD = 0.14$). The **prescription group** was composed by eight participants aged from 19 to 20 years ($M = 20.4$ ans, $SD = 0.8$). Their mean height was 1.79 m ($SD = 0.05$), their mean weight was 72.1 kg ($SD = 6.5$) and their mean swimming speed during 25 m breaststroke at maximal intensity was 0.97 m.s^{-1} ($SD = 0.07$). The protocol, approuved by the university ethic committee was explained to the participants who then gave their written consent to participate.

Two swimming coaches selected 32 swimmers in a pool of approximatively 90 swimmers who performed a 50 m breaststroke at a comfortable speed. The

exclusion criteria were the same as the experiment 3 (chapter 5). All swimmers were characterized as being at the first stage of motor learning (i.e. coordination), therefore were seeking for a basic functional relationship between limbs (K. M. Newell, 1986). Main characteristics of the swimmers at this stage of learning are a lack of glide with the body fully outstretched (i.e. with arms and legs outstretched), additionally to uniform movements (i.e. no acceleration in knee or elbow rotations) and a superposition of contradictory actions (e.g., leg propulsion with arm recovery) (Seifert, Leblanc, et al., 2011, 2010).

Learning program

All participants realized 16 learning sessions with three test sessions (pre-, post- and retention test). The entire program lasted 9 weeks, with two sessions per week. All participants performed at a different time during the day, in order to avoid any interaction between participants or groups. In a 25 m indoor pool, participants had to realize 10 x 25 m at sub-maximal speeds. They performed 5 x 25 m at 70% of their personal maximal speed and 5 x 25 m at 90% of their personal maximal speed. Trials [1, 3, 5, 7, 9] were performed at low swimming speed (i.e. 70%), and trials [2, 4, 6, 8, 10] were performed at high swimming speed (i.e. 90%). Each session lasted approximatively 35 min per participant and consisted in 10 min of warming up followed by the 10 trials with a start every 2 min 30 sec (a trial lasted 30 sec followed by 2 min rest). This sub-maximal speed, based on the maximal speed performed by each participant during the first session, corresponded to the working speed during all the learning process. Test sessions (i.e. pre-, post- and re-test) consisted in two trials at maximal speed followed by two trials performed at targeted speeds (i.e. 70% and 90% of maximal speed). The retention test was performed two months after the post-test. Participants were asked to avoid any breaststroke practice during the entire experiment (from pre-test to retention test), except during experimental sessions.

General goal of learning and specific instructions

For all the participants, the general goal of learning was to increase the stroke length (i.e. distance achieved per cycle) while maintaining the same sub-maximal speed. Learners were informed of this general goal at the beginning of each session. The basic rules of breaststroke swimming were reminded during the first session, and only if necessary after. If learners failed to respect the rules or the targeted speed, they were stopped by the experimenter and had to reperform the trial. After each trial,

learners were informed about their mean stroke length during the trial. No other information was given to the learners from the **control group** during the 16 sessions.

Even if Maxwell et al. (2000) considered that a control condition was not an implicit condition because learners develop explicit knowledge during the learning process (e.g., Hardy et al., 1996, showed that the control group developed explicit knowledge as much as the group receiving explicit instructions during learning), the objective was to avoid constraining the range of possibilities more than the free practice. In this perspective, the control group was considered as the less constrained during his exploration. For all the three other groups, the general goal of learning was also to increase the stroke length, but was accompanied to an additional temporary informational constraint focusing on the movement form:

Identically to the previous experiment (cf. chapter 5), the **analogy group** received an instruction through an analogy focusing on movement form: “glide two seconds with your arms outstretched”. This analogy was a “verbal representation of the task (...) relaying very little on explicit verbal instructions or action rules”. Instead of providing a set of verbal instructions on movement form during each phase of the swimming cycle (e.g. Wulf, Lauterbach, & Toole, 1999, p. 122), the present instruction was essentially directed towards the specific glide position of the arms, therefore considered as a focus on movement form. This instruction was unique and did not cover all the successive phases of the breaststroke cycle (i.e. leg propulsion, glide, arm propulsion, recovery).

The **pacer group** did not receive this analogy but had to follow a decreasing metronome (Aquapacer, Challenge and Response, Inverurie, UK) (Thompson, MacLaren, Lees, & Atkinson, 2002). More precisely, learners were asked “to have their arms outstretched forward when the signal sounds”. In order to cause a decrease in stroke length, the frequency of the metronome was decreased by 7% every two sessions, which represented a decrease of 2 or 3 points per level (in cycles per minute). The stroke frequency at the beginning of the learning process was the one freely expressed by participants during the pre-test. The amount of decrease was based on the decrease in stroke frequency exhibited by the other groups (i.e. control and analogy), but if the learner in the pacer group exhibited during his free practice a stroke frequency lower than his targeted frequency, this targeted frequency was decrease and the next levels were adjusted. The use of a visual metronome has been previously largely studied in bi-manual coordination (e.g. Tuller & Kelso, 1989; Yamanishi, Kawato, & Suzuki, 1980; Zanone & Kelso, 1992). For instance, Tuller &

Kelso (1989) and Yamanishi et al. (1980) showed that imposing an external rhythm specific to each oscillator lead to modifications in relative phase between these oscillators. However, even if participants were able to produce required phase lags, these “imposed” patterns were accompanied by increase in fluctuations of the coordination. Interestingly, authors revealed a systematic drift of imposed patterns towards initial stable patterns (i.e. in-phase and anti-phase), sign of an attraction of to-be-learned patterns towards the intrinsic dynamics. Zanone et Kelso (1992; 1997) also showed that it was possible to learn a new pattern of coordination by using a metronome. In the present experiment, the use of an auditory metronome was preferred to a visual metronome, as it appeared difficult to provide a visual signal underwater. The decrease in movement frequency of the master oscillator of the coordination (i.e. the oscillator that is in advance comparing to the second one, Faugloire et al., 2009) was supposed to lead to a global reorganization at the macroscopic level. The synchronization of the upper limbs to an external metronome has already been used in the rehabilitation of stroke patients in learning to walk (Ford, Wagenaar, & Newell, 2007). Orienting auditory signals towards the arms showed an effect on the entire motor organization of the walking pattern (i.e. including effect on the amplitude of rotation of the hip). In addition, without prescribing the movement form, the focalisation of the learner’s attention to an outstretched position of the arms was supposed to lead learners to reach and stay in this (hydrodynamic) position while waiting the signal. No other information about movement form was given to the learners of this group. Therefore, this group was considered as less constrained in his possibilities to explore than the analogy group. In case where swimmers encountered troubles to respect this double task (i.e. maintain the swimming speed and follow the metronome), experimenter explicitly asked them to principally maintain the speed and secondly try to follow the metronome.

The **prescription group** received additional information that prescribed the to-be-learned coordination during each phase of the swimming cycle. More precisely, it was indicated to learners four instructions:

1. “Keep your arms outstretched forward when you extend your legs”
2. “Glide with your arms and legs outstretched”
3. “Keep your legs outstretched when you flex your arms”
4. “Recover both arms and legs together”

Conversely to previous instructions considered as implicit, this set of instructions provided an explicit description of the to-be-learned pattern. The aim of

these explicit instructions was to indicate to learners the nature of the arm-leg coordination step after step during all the swimming cycles (e.g. Masters, Poolton, Maxwell, & Raab, 2008). This type of instruction was considered as providing too much narrow information therefore limiting the possibility of exploration (Davids et al., 2008). The use of four instructions was deemed as sufficient to prescribe the coordination, without providing too many information to the learners. Indeed, previous experiments providing explicit instructions usually provided too many information regarding the unique information provided through the analogy (e.g., 12 explicit instructions vs. 1 analogy [Liao & Masters, 2001], 6 explicit instructions vs. 1 analogy [Masters et al., 2008; Poolton, Masters, & Maxwell, 2006], 8 explicit instructions vs. 1 analogy [Lam, Maxwell, & Masters, 2009]). The idea was then to limit this difference in the amount of provided information between the experimental groups (e.g., Chow, Koh, Davids, Button, & Rein, 2013). This experimental group was considered as the most constrained in his exploration.

All participants performed 16 learning sessions, with 10 trials during each session (five at low swimming speed and 5 at high swimming speed). The control group performed all the trials in the free condition, namely only with the general goal of learning as instruction, whereas the other groups performed the first two trials of each session in free condition (in order to assess the effect of the constraint on the free practice), and the other trials [3-10] with the additional constraint (Figure 31).

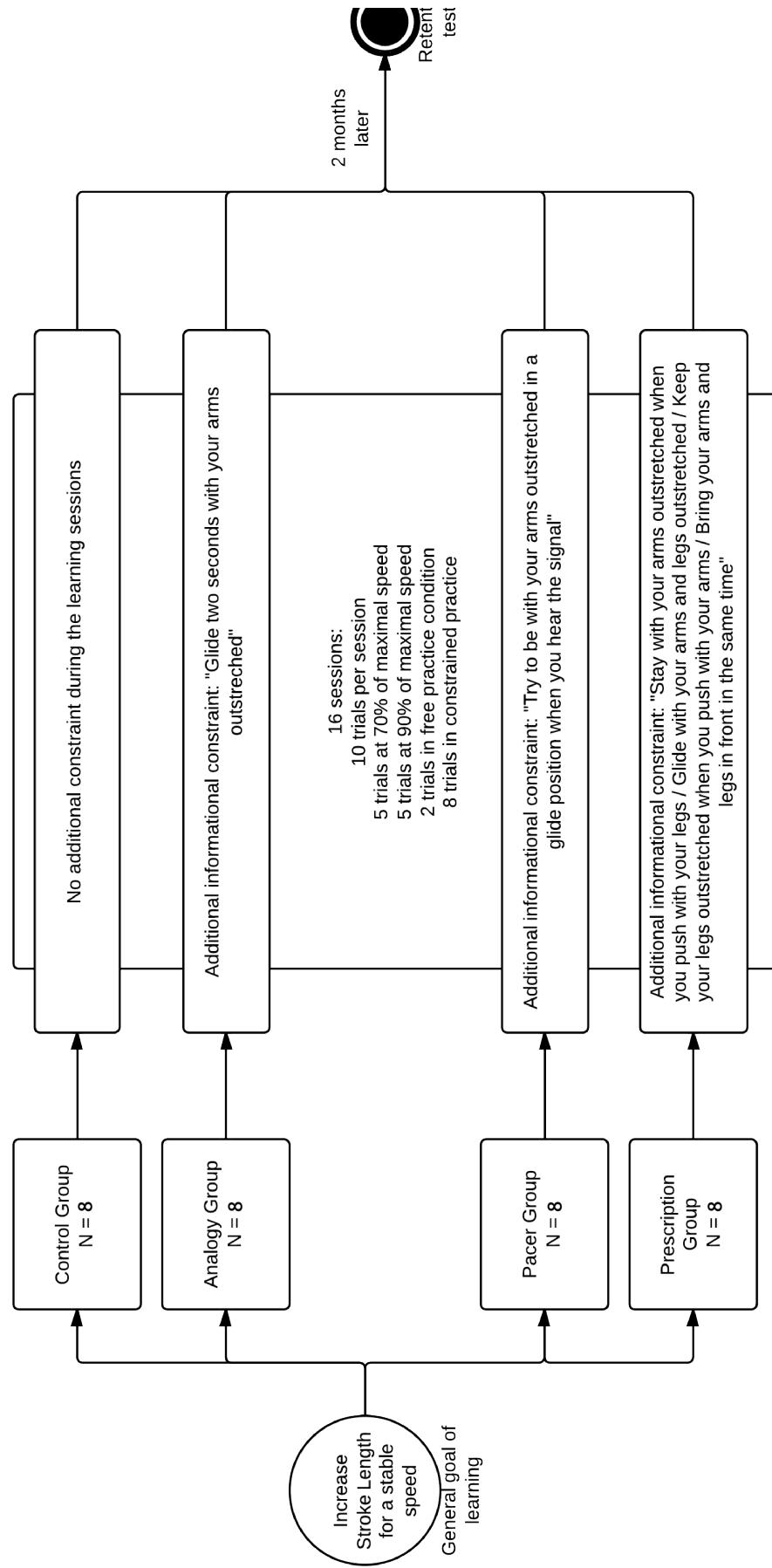


Figure 31. Presenation of the learning design with the four learning conditions

Measurement material

Motion sensors. Participants were equipped with inertial central *MotionPod3* including 3-D accelerometers, 3-D magnetometers and 3-D gyroscopes (Movea, Grenoble, France) in a modified version also including a data logger (Figure 32, detailed information about measurement validations in annex A) (Jégo, Paljic, & Fuchs, 2013; Seifert, L'Hermette, et al., 2011). The acquisition frequency was 200 Hz.



Figure 32. Modified version of MotionPod3 including a data logger
(Dimensions: 44*18*22 mm).

Four motion sensors were positioned on the left side of the swimmers, respectively on the forearm (posterior surface of the proximal portion), the arm (posterior surface of the distal portion), the thigh (anterior surface of the distal portion) and the leg (anterior surface of the proximal portion), in order to place the sensors in direct contact with a bony part of the limb. At the beginning of each session, the positioning of the motion sensors was adjusted to a black marker defining the location of the sensor during the last session. Last, the two limbs equipped with sensors wore strands of swimsuits in order to limit resistances due to the presence of the sensors (Figure 33). An unilatral measurement was deemed as accurate due to the exclusion of swimmers that did not perform symmetrical movements.



Figure 33. Lower limb (left) and upper limb (right) equipped with motion sensors and swimsuits.

Once the swimmer was equipped, he entered the water in the second line (i.e. at least two meters far from the wall to avoid any magnetic disturbance). Thereafter, each participant had to strictly follow the same protocol during each trial: a) swimmers performed 3 slaps on the sensor positioned on the left arm in order to signal the start of a trial; b) he thereafter had to stay immobile 10 seconds in order to calibrate the motion sensors with the reference position (i.e. 180° with arms and legs); c) the swimmer performed again 3 slaps on the sensor positioned on the arm and started his trial (he had to avoid a long push from the wall, in order to perform a swimming cycle before 5 m); d) directly at the end of the trial, the swimmer had to perform 4 slaps on the sensor in order to signal the end of the trial; e) the swimmer could then go out of the water and walk to the start of the start of the swimming pool. This protocol had to be respected during the 10 trials of each session.

Once the records were done, the data were uploaded and synchronized *a posteriori* with Matlab r2009b. Each trial was then recognized by detection of the slaps (saturation of the accelerometric signal), and the 10 trials per learners were exported. Thereafter, elbow and knee angles were computed for each trial by using *MoveaLab* (Movea, Grenoble, France) (Figure 34) that calculated relative angle between two sensors.

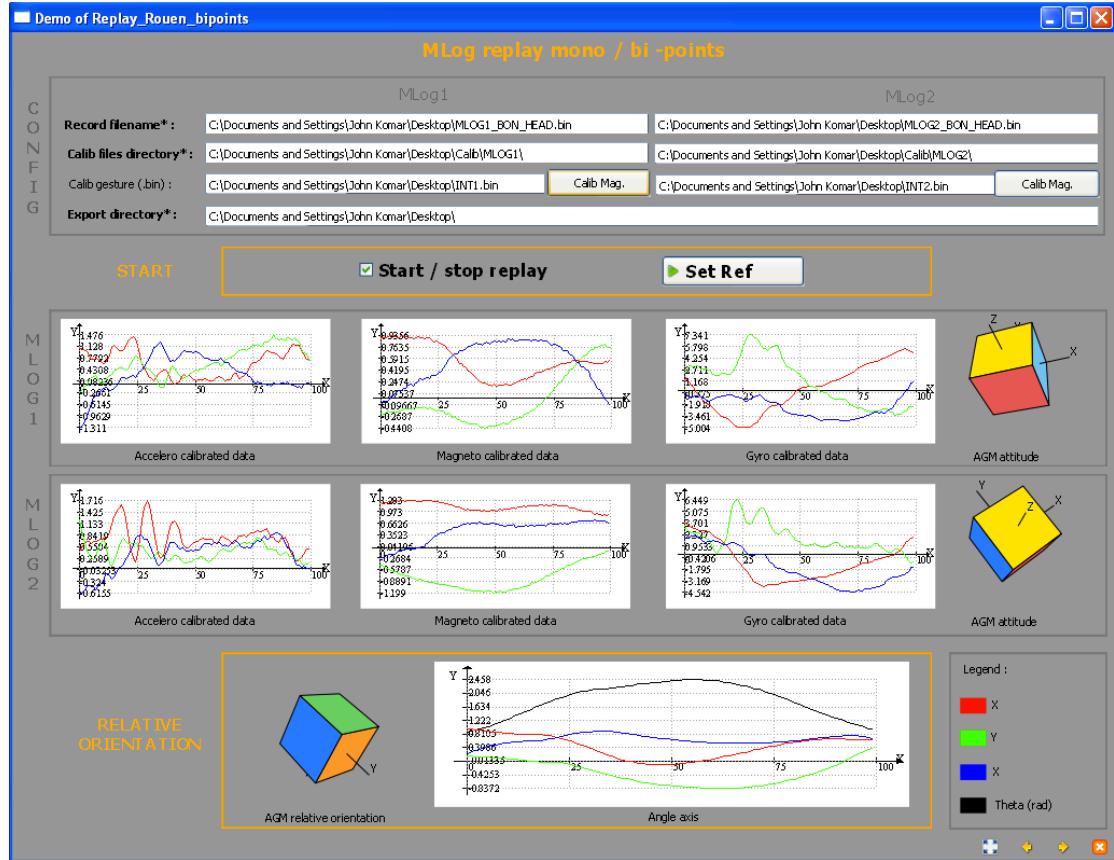


Figure 34. Screenshot of the MoveaLab calculating relative orientation between two sensors (here between MLOG 1 & MLOG 2).

Time series representing knee and elbow angles were then computed (Figure 38). These time series were filtered with a low-pass Fourier filter (cutoff frequency 8 Hz) and cut cycle per cycle (i.e. one cycle beginning with a maximal knee flexion and finishing with the next maximal knee flexion). The first two cycles as well as the last two cycles were removed in order to avoid any acceleration or deceleration effect. For each trial, knee and elbow angular positions for 3 to 17 cycles were kept to characterize the coordination. The variability of the number of cycles was mainly due to the swimming speed (i.e. the stroke length was higher at low swimming speed, leading to less cycles performed).

Video analysis. In addition to angular measurement with motion sensors, a video analysis was performed essentially during the pre-test, post-test and re-test in order to keep a visual feedback of the observed behaviors. Therefore, a trial at low swimming speed and a trial at high swimming speed have been recorded during each test session.

Coordination assessment

The arm-leg coordination was assessed by The Continuous Relative Phase (CRP). The CRP was computed based on elbow and knee angles in the same way as previous experiments (cf. chapter 3, p. 64).

Assessment of the variability of the behavior

The variability of the coordination as well as the variability of each independent oscillator (i.e. elbow and knee) was assessed with the Cauchy index (Chen et al., 2005; Rein, 2012). This index is based on the Euclidian distance that separates two successive cycles during a trial. Cauchy index was calculated as follow (Equation 9):

$$C_i = \frac{1}{K * (N-1)} \sum_{n=1}^N \sqrt{\sum_{k=1}^K (x_{kn(i+1)} - x_{kn(i)})^2} \quad [9]$$

where C_i represents the number of Cauchy for the cycle i , K the number of variables (i.e. the value of CRP in the present case), N the number of values per variables during one cycle (i.e. 100 in the present case) (Chen et al., 2005; Rein, 2012). Conversely to the Root Mean Square, this index informs about the cycle per cycle variability, considered as representing the amount of cycle per cycle exploration. Thus, a small value of C_i informs about similar successive patterns of coordination (or elbow/knee patterns). Without defining the nature of a pattern, this approach is based on the assumption that the variations of the movement trajectory decrease with learning, showing a convergence of the behaviour towards a specific pattern.

Performance assessment

During each trial, the time during 15 m (t_{15} in seconds, from 5 to 20 m in the swimming pool) was assessed and the average stroke frequency during six cycles (F in $\text{cycles} \cdot \text{min}^{-1}$) was assessed with a frequency counter. In the meantime, the mean swimming speed (v , in $\text{m} \cdot \text{s}^{-1}$) during 15 m was calculated and the average stroke length of the trial (A , in m) was calculated as follow (equation 10):

$$A = \frac{v}{F} \quad [10]$$

$$\frac{60}{60}$$

In addition, the instantaneous stroke frequency (f , in Hz) was assessed for each cycle from the duration of each cycle (measured with the motion sensors) following equation 11:

$$f = \frac{1}{\text{durée du cycle}} \quad [11]$$

Considering the linear relationship between v , A and F (equation 8) and the equality $f = F/60$, the decrease in the instantaneous stroke frequency during learning was considered as reflecting the increase in stroke length (mainly because the swimming speed was constant during the entire learning process). The temporal dynamics of the performance (i.e. the increase in stroke length, not measured by the motion sensors) was defined by the temporal dynamics of f .

Dependant variables

Nature of the behaviour. For each cycle performed by the learners during the learning process, the nature of the behaviour was assessed by the time series of CRP during the cycle, resampled in duration in order to have 100 values for each cycle.

Variability of the behaviour. The variability of the behaviour was assessed based on: a) Cauchy index of the CRP; b) Cauchy index of the knee angular positions; Cauchy index of the elbow angular positions.

Performance. Three performance variables were used: a) the mean swimming speed in the two different speed conditions, in order to validate the task for each learner; b) the mean stroke length during each trial; c) the instantaneous stroke frequency during each cycle.

Data analysing

Determination of different profiles of coordination. A cluster analysis was used in order to differentiate the patterns of coordination exhibited by learners (Rein, Button, et al., 2010; Rein, 2012). The resampled time series (i.e. 100 values) of CRP from the entire experiment (i.e. all the cycles, all the trials, all the participants, all the sessions and all the groups) have been used to compute the cluster analysis. Such a cluster analysis allows partitioning the entire set of cycles into meaningful sub-groups or clusters, whereas the “real” number of groups is unknown *a priori*. The Fisher-EM algorithm has been used for the present experiment (Bouveyron & Brunet, 2012a, 2012b). This kind of EM algorithm (*Expectation Maximisation*) is based on a probabilistic model that considers the data as derived from a mixture of probabilistic distributions. The principal advantage of this model-based algorithm is that it allows the computation of very large data sets, unlike a hierarchical clustering as previously used (cf. chapter 4). The Fisher-EM algorithm is an iterative cluster algorithm that projects the data in a new subspace at each iteration in such way that emerging clusters maximize the Fisher information (i.e. maximize the inter-cluster distance

while minimizing the intra-cluster distance). Conversely, the Principal Component Analysis also proposes a new projection but only in maximizing the variance without considering the clusters. In addition with the Fisher-EM algorithm, the dimension of the new subspace can be modulated by a “sparsity” parameter that selects a limited number of variables or weighs the variables that mostly explain the clustering. Thus, this algorithm allows both to determine the number and weight of the discriminative variables (i.e. the sparsity) (Bouveyron & Brunet, 2012a; Dasgupta & Raftery, 1998), as well as the number of clusters that best fits the data (i.e. that maximizes the Fisher information) (Campbell, Fraley, Murtagh, & Raftery, 1997).

The different possible models were assessed directly by comparison of the BIC criterion (*Bayesian Information Criterion*) of each model. This BIC criterion allows validating both the sparsity (i.e. the weight of each value) as well as the number of cluster that maximize the Fisher information. Practically, one has to perform the cluster analysis for all the possible models, namely for a number of cluster from 2 to M (where M is the maximal number of cluster that would make sense [i.e. finding 67 clusters would not have any sense]); and for a sparsity that gives higher weight to explanatory variables (e.g. the value of CRP at the beginning of the cycle). Then, the model that best fits the data is the one that provides the first local minimum in the BIC vector. In other words, the optimal model (i.e. in terms of sparsity and number of clusters) is the first model leading to a plateau in the value of BIC. To summarize, the approach consists in three steps:

1. Defining: i) the maximal number of clusters (M) that would be the limit that make sense (i.e. more clusters would be impossible to explain or simply would not have any sense), and ii) an index of sparsity that determines relevant discriminative variables that have a signification in terms of coordination
2. Performing the cluster analysis for a potential number of cluster from 2 to M , and calculate the BIC index for each model.
3. Finding in the BIC vector the first local minimum (sometimes global) indicating the model that best fits the data (both in terms of number of clusters and sparsity).

Switching ratio. The switching ratio (SR) (Chow, Davids, Button, & Rein, 2008, adapted from Wimmers, Savelbergh, Beek, & Hopkins, 1998) informed about the preferential use of a pattern during a trial. Un change can theoretically occur between

two successive cycles, for instance in a trial containing 10 cycles, the total number of possible changes is 9. The switching ratio then corresponds to the actual number of observed changes divided by the theoretical maximal number of possible changes. For a trial containing 10 cycles corresponding respectively to clusters [1,3,2,1,3,2,2,2,2,1], the switching ratio is 6:9 (or 0.667). Conversely for the trial corresponding to clusters [1,2,1,2,1,2,1,3,2,1], the switching ratio is 9:9 (or 1). SR gives information about the global movement variability within a trial.

Stability criterion of a pattern of coordination. Based on the work of Wimmers et al. (1998), Chow et al. (2008) defined the presence of a stable pattern if two conditions are respected. More precisely, a pattern of coordination was considered as stable when his occurrence (i.e. percentage of presence within a trial) was more than 78% and his SR was less than 0.235 (i.e. defining few switches).

From this stability criterion, the three regimes of stability defined by Kelso (1995; 2012) were defined as follow, namely mono-, meta- or multi-stability:

- Mono-stability: an occurrence higher than 78% and a SR lower than 0.235; for instance a trial like the following [C1,C1,C1,C1,C2,C1,C1,C1,C1,C1], with a SR = 0.2 and an occurrence of 91% corresponds to a stable regime of the pattern C1.
- Multi-stability: an occurrence higher than 30% and a SR lower than 0.235. This threshold of 30% has been defined arbitrarily, considering that the presence of more than three different patterns could not be considered as a multi-stable regime (even if four patterns can be present each with 25% occurrence); for instance a trial like the following [C1,C1,C1,C1,C1,C4,C2,C2,C2,C2], with a SR = 0.2 and an occurrence of 45% for the pattern C1 and 45% for the pattern C2 corresponds to a mutli-stable regime of the patterns C1 and C2 (bi-stability).
- Metastability: a SR between]1 - 0.235[, independently of the occurence ; for instance a trial like the following [C4,C3,C3,C1,C1,C2,C2,C4,C3,C3], with a SR = 0.5 and an occurrence of 18% for patterns C1, C2 et C4, and of 45% for the pattern C3 corresponds to a metastable regime.
- Instability or absence of coupling: a SR = 1.0 (i.e. a change of pattern at every cycle) and an occurrence lower than 22% (i.e. the opposite of stability, which corresponds to the presence of at least five different patterns within the 11 possibles); for instance a trial like the following

[C4,C2,C8,C1,C3,C7,C9,C11,C2,C5,C6], with a SR = 1 and a maximal occurrence of 17% for the pattern C2 corresponds to an unstable regime or to an absence of coupling between the oscillators.

Exploration/exploitation Ratio. Based on the time series of exhibited patterns of coordination, a transition matrix was calculated for each participant. This transition matrix defines the transitions that occurred between the cycle t and the cycle $t+1$, and therefore includes 121 different transitions (11 x 11; defining 11 different patterns that can follow themselves or one of the 10 other patterns). On this matrix, the diagonals represent the repetition of identical patterns (e.g., 1-1, 2-2, 3-3,..., 11-11), called “exploitation”, whereas all the other (110) transitions represent the use of a different pattern at the cycle $t+1$ comparing to the cycle t , called “exploration”. The exploration/exploitation ratio has then been calculated as the number of occurrence of “exploration” divided by the number of occurrence of “exploitation”. A high exploration/exploitation ratio (E/E ratio) refers to a participant that explores a lot and conversely, whereas a ratio equal to 1 defines an identical amount of exploration and exploitation. This E/E ratio informs about the global quality of an instruction to bring the participants to leave their initial behaviour in order to explore new patterns of coordination.

Statistical analysis. Before all statistical analysis, normality of distributions (Kolmogorov-Smirnov test) and the homogeneity of variance (Levêne’s test) were verified. In addition, as the participants were asked to perform a specific distance, they showed different numbers of cycles performed during their trials. Therefore in order to perform statistical analysis on these unbalanced data, each trial has been resampled with 20 cycles by a random sampling with replacement from the set of realized cycles. Each session therefore corresponded into 10 trials of 20 cycles.

First, in order to compare the general effect of learning on the performance (i.e. stroke length), a three-way ANOVA for repeated measures (session: within participants [pre-, post-, re-test] x group: between participants [control, analogy, pacer, prescription] x speed condition: within participants [low swimming speed, high swimming speed]) was used, mainly during the free practice trials (i.e. trials 1 and 2 of each session, when all participants had only to seek for high stroke length). In order to increase the power of the tests, the increase of performance between the sessions

was also investigated through the decrease of the stroke rate, for which one value per cycle was assessed (whereas only one value for each trial was assessed for the stroke length). Therefore, a three-way ANOVA for repeated measures (session: within participants [1-17] x group: between participants [control, analogy, pacer, prescription] x speed condition: within participants [low swimming speed, high swimming speed]) was performed mainly during the free practice trials (i.e. trials 1 and 2 of each session, when all participants had only to seek for high stroke length).

In order to compare the effect of the different learning conditions on the variability of the CRP (Cauchy index) and on the switching ratio during the learning process, three-way ANOVA for repeated measures (session: within participants [1-16] x group: between participants [control, analogy, pacer, prescription] x speed condition: within participants [low swimming speed, high swimming speed]) were used, but this time mainly during the constrained trials (i.e. trials 3-10, when participants had to respect the additional constraints acting on them).

The effect of the constrained practice (trials 3-10) *vs.* free practice (trials 1-2) during each session, the 8 constrained trials were averaged as well as the 2 free trials were averaged (in order to limit the imbalance in terms of amount of data), and a four-way ANOVA was used (session: within participants [1-16] x group: between participants [control, analogy, pacer, prescription] x speed condition: within participants [low swimming speed, high swimming speed] x condition of practice: within participants [free, constrained]) but only the effect of the condition of practice (free *vs.* constrained) was investigated, considering that the other effects were already investigated with more statistical power through previous three-way ANOVA.

In order to investigate the differences in variability between elbow oscillations (i.e. elbow Cauchy index) and knee oscillations (i.e. knee Cauchy index), a four-way ANOVA (session: within participants [1-16] x group: between participants [control, analogy, pacer, prescription] x speed condition: within participants [low swimming speed, high swimming speed] x oscillator: within participants [knee, elbow]) was used following previous studies (Goulet, Bard, & Fleury, 1989; Mecheri, Gillet, Thouvareq, & Leroy, 2011) but only the effect of oscillator (knee *vs.* elbow) were investigated.

Last, a one-way ANOVA (fixed factor: group [control, analogy, pacer, prescription]) has been performed in order to test the difference between groups concerning the E/E ratio. In the case of the normality and homogeneity of variance were not verified, non-parametric tests were used, namely a Kruskal-Wallis followed

by pairwise comparisons with a Mann-Whitney test. In case of the use of ANOVA with repeated measures, *p* values were corrected if necessary for a possible deviation from sphericity with a Greenhouse-Geisser (ϵ) correction. All tests were conducted with SPSS 20.0 (IBM statistics) and Matlab R2009b. For all significant effect, the effect-size was estimated with partial η^2 (Cohen, 1988). A $\eta_p^2 = 0.02$ defines a small effect, $\eta_p^2 = 0.13$ defines a medium effect and $\eta_p^2 = 0.26$ defines a large effect (Bakeman, 2005).

Summary about the indicators of movement variability :

- *Coordination patterns*: qualitative information about the nature of arm-leg coordination. The assigned pattern corresponds to the most similar coordination pattern comparatively to the performed pattern.
- *Cauchy index*: quantitative information about the amount of exploration (in degrees of CRP). It is possible to show a low Cauchy index but notwithstanding show qualitativ changes in terms of patterns of coordination.
- *Switching ratio*: informs about the global vriability of the coordination patterns observed during a trial.
- *Exploration/exploitation ratio* : global information on the propensity of a learner to leave its initial behavior and explore other patterns of coordination.
- *Stability regime*: informs about the global regime exhibited by the learner during a trial (i.e. mono-, multi-, méta-, or instability).

Results

Participants 3 from the control group, 5 from the analogy group, 2 and 4 from the pacer group and 1 and 3 from the prescription group failed to respect the frequency of the sessions due to diverse reasons (e.g. injuries). Therefore, these participants have been enterily removed from the panel (Table 7).

Performance and completion of the task

Completion of the task. Table 7 shows for each participant the targeted speed that participant had to follow, the mean actually achieved speed and the percentage of error between the achieved speed and the targeted speed. Even if all participants were able to perform 10 trials with less than 5% error regarding the targetted speed, additional instructions made the respect of the speed more difficult for the analogy, pacer and prescription group. Indeed, while 16 trials (for 1120 in total) have been canceled for the control group because these trials ere too slow or too fast, this number was 69 (for 1120) for the analogy group, 92 (for 960) for the pacer group and 67 (for 960) for the prescription group.

Table 7. Presentation for each participant of the targetted speed, the realized speed and the mean percentage of error between targeted and realized speed.

Group	Participant	Low swimming speed			High swimming speed		
		Target speed (m.s ⁻¹)	Mean realized speed (m.s ⁻¹)	Mean error to the target (% of target speed)	Target speed (m.s ⁻¹)	Mean realized speed (m.s ⁻¹)	Mean error to the target (% of target speed)
Control	1	0.6	0.62 ± 0.02	2.4 ± 1.9	0.77	0.76 ± 0.03	3.0 ± 0.9
	2	0.58	0.60 ± 0.03	3.3 ± 0.9	0.74	0.74 ± 0.03	2.6 ± 0.7
	3	/	/	/	/	/	/
	4	0.63	0.61 ± 0.03	2.2 ± 0.6	0.81	0.80 ± 0.03	2.1 ± 0.5
	5	0.63	0.65 ± 0.03	2.9 ± 1.1	0.81	0.82 ± 0.02	3.1 ± 0.8
	6	0.63	0.62 ± 0.03	3.2 ± 1.2	0.81	0.82 ± 0.03	3.6 ± 2.1
	7	0.69	0.67 ± 0.04	3.8 ± 0.9	0.89	0.88 ± 0.03	2.4 ± 0.8
	8	0.57	0.57 ± 0.03	3.1 ± 1.1	0.73	0.72 ± 0.03	3.0 ± 1.1
Analogy	1	0.68	0.68 ± 0.03	3.1 ± 0.3	0.87	0.87 ± 0.02	2.1 ± 1.4
	2	0.67	0.67 ± 0.03	3.2 ± 1.5	0.86	0.86 ± 0.04	2.5 ± 0.7
	3	0.68	0.67 ± 0.03	4.02 ± 2.2	0.88	0.87 ± 0.02	2.5 ± 1.7
	4	0.62	0.63 ± 0.03	3.1 ± 1.9	0.79	0.80 ± 0.03	3.1 ± 0.8
	5	/	/	/	/	/	/
	6	0.64	0.62 ± 0.03	2.6 ± 1.4	0.82	0.84 ± 0.03	2.4 ± 1.1
	7	0.68	0.67 ± 0.04	1.8 ± 1.1	0.88	0.88 ± 0.03	3.1 ± 2.0
	8	0.62	0.63 ± 0.02	3.1 ± 1.9	0.79	0.78 ± 0.03	2.9 ± 1.1
Pacer	1	0.63	0.63 ± 0.03	3.4 ± 1.1	0.84	0.86 ± 0.05	3.3 ± 2.1
	2	/	/	/	/	/	/
	3	0.69	0.67 ± 0.04	3.6 ± 2.0	0.89	0.90 ± 0.03	2.7 ± 1.4
	4	/	/	/	/	/	/
	5	0.75	0.74 ± 0.04	2.5 ± 0.6	0.96	0.97 ± 0.04	2.2 ± 0.9
	6	0.71	0.69 ± 0.03	2.7 ± 0.7	0.91	0.93 ± 0.03	3.4 ± 1.3
	7	0.73	0.72 ± 0.03	1.9 ± 0.6	0.93	0.95 ± 0.04	3.3 ± 1.6
	8	0.69	0.69 ± 0.03	3.2 ± 1.8	0.89	0.88 ± 0.05	2.3 ± 1.7
Prescription	1	/	/	/	/	/	/
	2	0.66	0.68 ± 0.01	1.9 ± 0.6	0.85	0.85 ± 0.02	1.7 ± 0.5
	3	/	/	/	/	/	/
	4	0.67	0.68 ± 0.03	3.1 ± 1.3	0.86	0.86 ± 0.02	2.3 ± 0.4
	5	0.67	0.68 ± 0.03	2.1 ± 1.0	0.86	0.84 ± 0.02	1.8 ± 0.6
	6	0.71	0.72 ± 0.02	1.9 ± 0.5	0.91	0.91 ± 0.03	2.3 ± 0.7
	7	0.71	0.71 ± 0.03	2.9 ± 0.6	0.91	0.92 ± 0.03	3.0 ± 2.1
	8	0.7	0.72 ± 0.04	2.3 ± 0.8	0.9	0.90 ± 0.03	2.4 ± 1.3

Performance. Three-way ANOVA concerning the evolution of stroke length only during the free trials (trials 1 and 2 during each session, when the instruction for each participant was to seek for higher stroke length) showed a significant effect of test session (pre, post- or re-test) ($F(2,44) = 188.38, p < .001, \eta_p^2 = .895$), and a significant effect of speed condition ($F(1,22) = 68.23, p = .001, \eta_p^2 = .756$).

In addition, an interaction effect test session × speed ($F(2,44) = 43.47, p < .001, \eta_p^2 = .663$) appeared. Post-hoc tests showed that the four groups were not different in terms of stroke length during the pre-test (first session), and they all increased their stroke length during the post-test (session 16) ($p < .001$) and the re-test (session 17) ($p < .001$), whereas no difference appeared between the post-test and the

re-test ($p = .884$) (Figure 35). However, the four groups exhibited during the post-test and the re-test a higher stroke length at low swimming speed than at high swimming speed ($p < .001$), when no speed effect appeared during the pre-test (Figure 36).

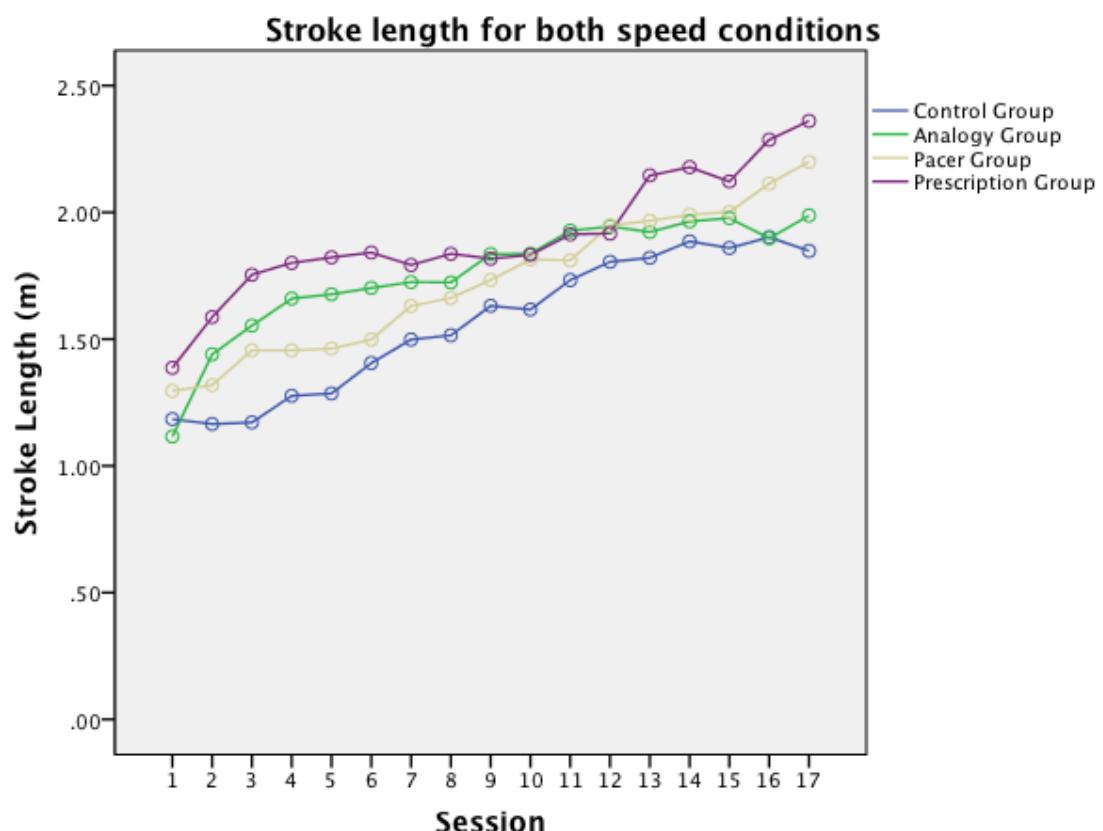


Figure 35. Stroke length for both speed conditions as a function of group and session.

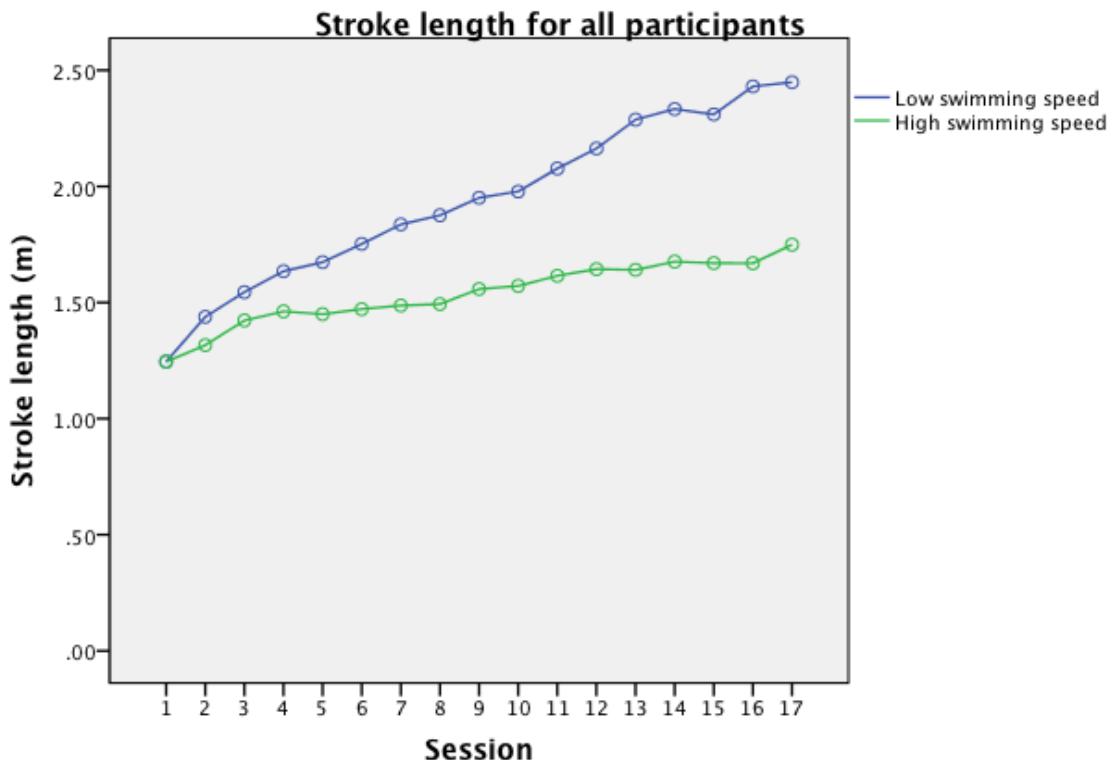


Figure 36. Stroke length for both groups as a function speed condition and session.

A three-way ANOVA comparing the stroke frequency during each session validated previous results obtained on stroke length between pre-, post- and re-test, namely that the four groups exhibited an identical stroke frequency during session 1 (all $p_s > .98$), all decreased their strok frequency (i.e. increased their stroke length) during session 16 and 17 (all $p_s < .001$). A session per session analysis showed different pathways in the decrease of the frequency. Indeed, a sessions effect ($F(7.06,3642.93) = 1081.34, p < .001, \eta_p^2 = .677, \epsilon = .441$), a speed effect ($F(1,516) = 1223.91, p < .001, \eta_p^2 = .959$) and a group effect ($F(3,516) = 71.18, p < .001, \eta_p^2 = .293$) appeared significant. In addition, a triple interaction was also significant ($F(26.98,4641.74) = 35.03, p < .001, \eta_p^2 = .169, \epsilon = .562$) and post-hoc tests revealed the different profiles.

Low swimming speed. Analogy and prescription groups showed a similar decrease in stroke frequency, with a strong decrease during the 3 firsts sessions (sessions 2 ≠ 1, 3 ≠ [1,2]), followed by a slight decrease thereafter (4 ≠ [1,2], 5 ≠ [1,2], 6-12 ≠ [1,2,3]). For these groups, the decrease stopped after session 8 (i.e. no difference between the post-test and sessions [8-15]) (Figure 37). The control group showed a delay at the beginning of the learning process, as the first significantly different session in terms of frequency is the session 3. Thereafter, the decrease is linear until session 16: a significant difference appeared every 2 sessions. This control

group exhibited a decrease in frequency until session 13 (i.e. no difference between session 16 and [14-15]). Last, the pacer group showed a decrease in frequency since session 2, but thereafter exhibited different plateaus in the decrease of frequency: (2,3,4 ≠ 1), then (5,6,7,8 ≠ [1-4]), then (9,10,11 ≠ [1-8]) and (12-17 ≠ [1-11]).

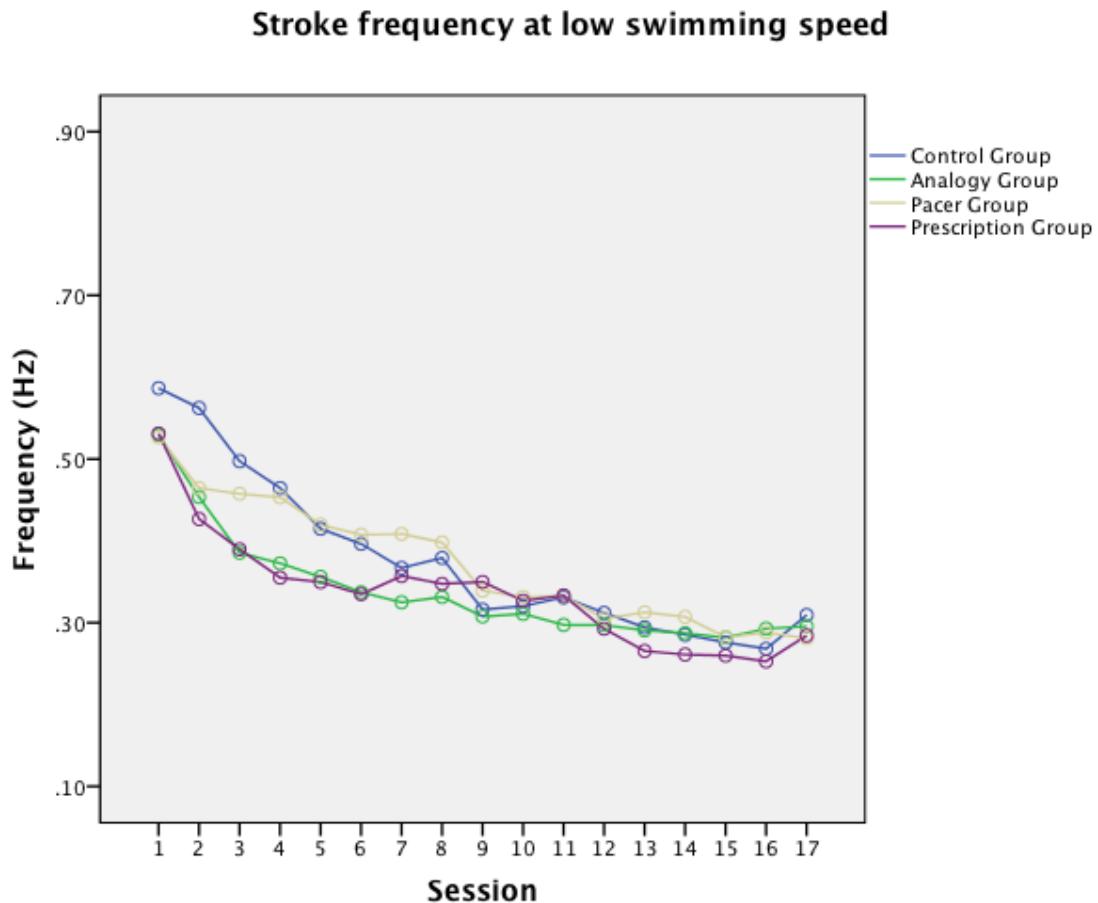


Figure 37. Stroke frequency exhibited by swimmers in low swimming speed condition in function of group and session.

High swimming speed. Identically to low swimming speed, analogy and prescription groups showed a strong decrease in frequency at the beginning of the learning process ($2 \neq 1$; $3 \neq [1,2]$; $4 \neq [1,2,3]$). Interestingly, these groups showed no difference between session 4 and session 16 (post-test) (Figure 38). In fact, learners from these groups achieved rapidly their minimal frequency and showed thereafter (between sessions 5-16) only fluctuations of their frequency. Identically to low swimming speed, the control group showed a delay in the decrease of frequency, that appeared only since session 3 ($3 \neq [1,2]$). However, this group achieved his minimal frequency since session 7, when he reached his minimal frequency only at session 13 in low swimming speed. The pacer group showed an important variability during the

first 5 sessions ($1 < 2 > 3 < 4 > 5$). This group then stabilized his frequency between sessions 5 and 8 to show a strong decrease only between sessions 8 and 10 followed by a second plateau between sessions 10 and 14. This pacer group showed his last decrease between sessions 15 and 16 (i.e. before the post-test). Finally, both analogy and pacer group showed a decrease in stroke frequency between post-test and re-test.

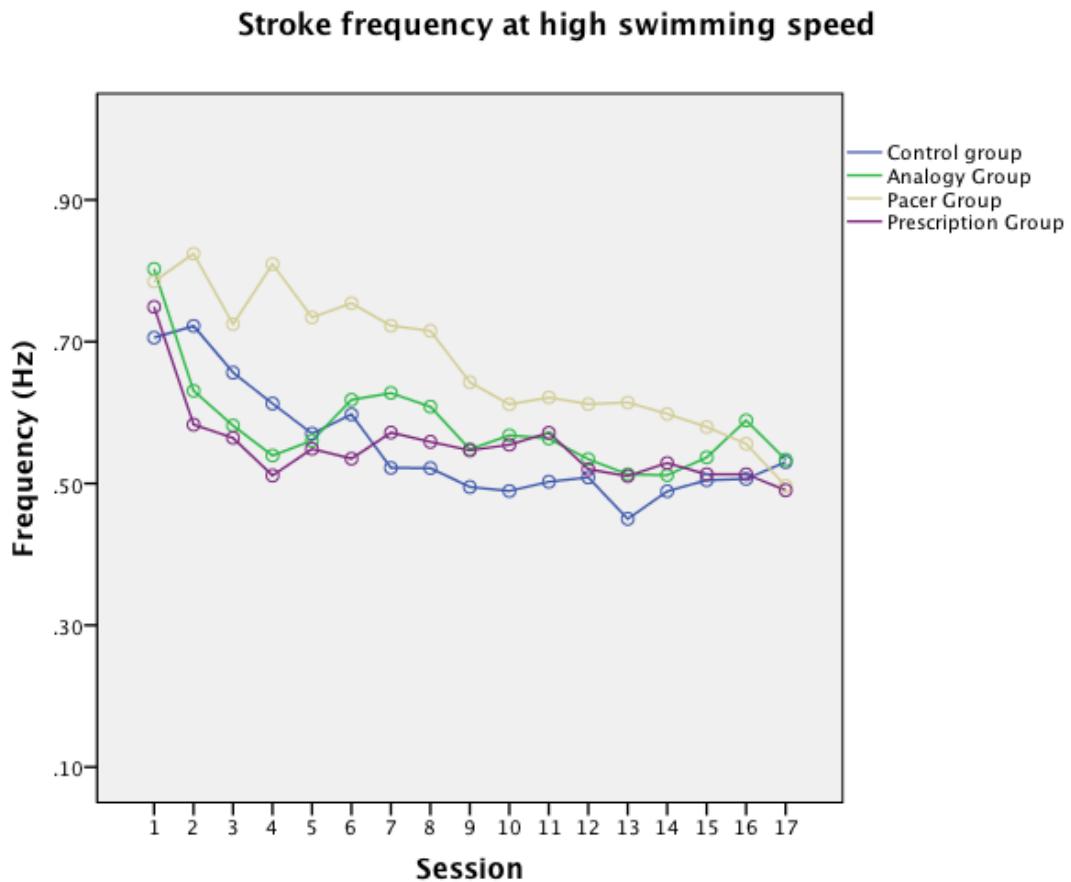


Figure 38. Stroke frequency exhibited by swimmers in high swimming speed condition in function of group and session.

The four-way ANOVA focusing principally on the effect of the constrained practice (trial 3-10) vs. The free practice (trial 1 and 2) showed a significant effect of the condition of practice ($F(1,22) = 38.246, p < .001, \eta_P^2 = .635$) as well as triple interactions practice condition \times speed \times group ($F(3,22) = 17.10, p < .001, \eta_P^2 = .700$) and practice condition \times Session \times group ($F(45,330) = 3.36, p < .001, \eta_P^2 = .315$). Post-hoc tests showed that in high simming speed condition, the pacer group had a higher frequency during the free trials comparatively to the constrained trials ; this was the case mainly during the 8 firsts sessions ($p < .001$) (e.g. Figure 39, and appendices for all the participants from the pacer group). This difference between free practice and constrained practice also appeared for the analogy and prescription

groups, but essentially during the first session ($p_s < .009$). The control group showed no difference between trials 1-2 and trials 3-10, as all trials were freely performed. This result validated the fact there was no order effect on the performance.

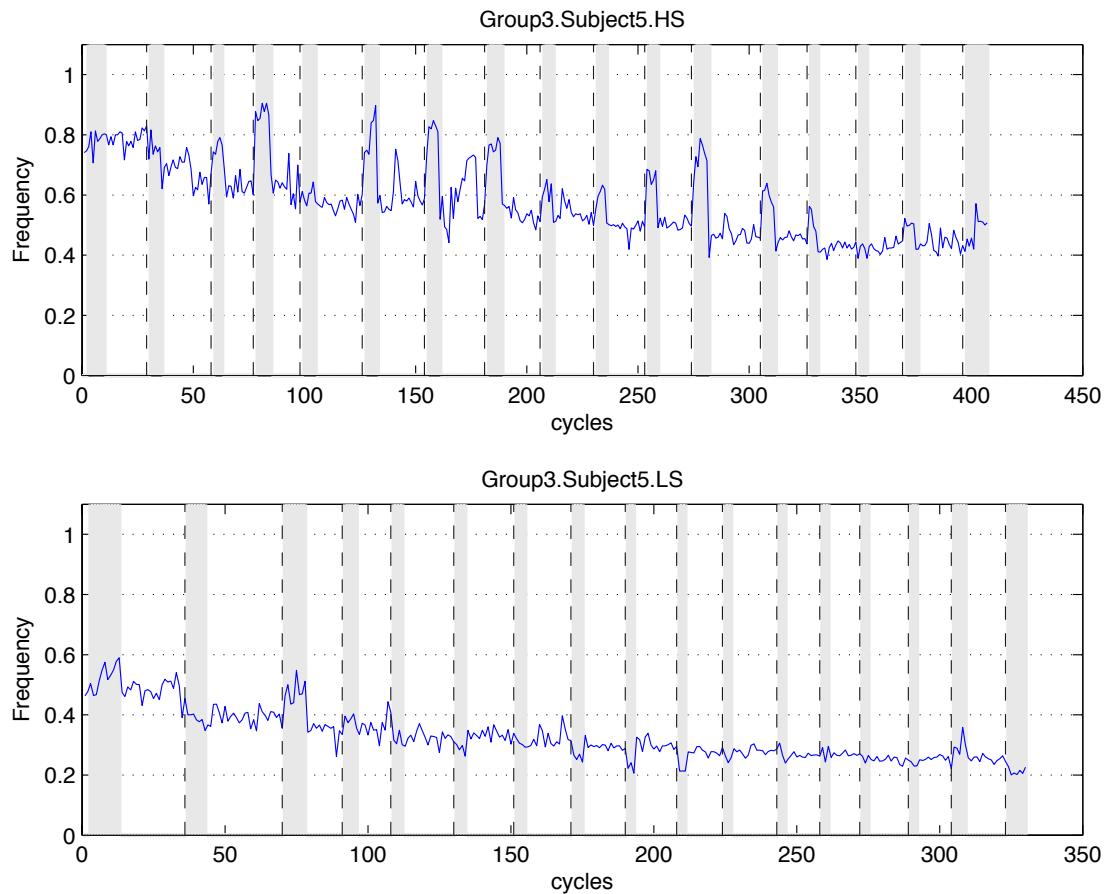


Figure 39. Cycle per cycle stroke frequency for the participant 5 of the pacer group, showing in high swimming speed condition (top) the difference of frequency between free trials (grey) and constrained trials (white).

Coordination profiling

The BIC criterion ([2-16] potential clusters) showed that the optimal number of clusters that best fitted the data was 11. Indeed, 11 is the first value of the plateau in the BIC vector (Figure 40).

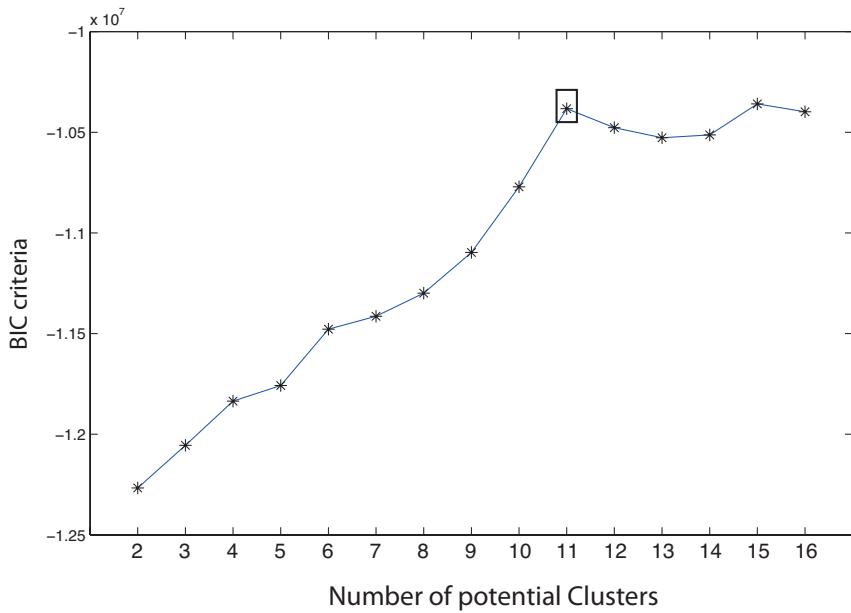


Figure 40. BIC Criterion for a number of potential clusters from 2 to 16 (the square represents the first local minimum).

In addition, the sparcity showed four zones that principally discriminated the clusters (Figure 41):

- a) beginning of the cycle [1-10 % of cycle duration]: this portion informs about the nature of the coordination during the leg extension phase (i.e. propulsion), namely that during this period, the theoretically effective coordination corresponds to an anti-phase mode (elbows in maximal extension and knees in maximal flexion).
- b) between 36-42% of the cycle duration: this portion indicates the nature of the coordination during the glide phase, namely that a CRP value at 0° indicates a streamlined glide position (knees and elbows maximally extended), whereas a positive value indicates that knees are slightly flexed during the glide (i.e. a less hydrodynamical profile). In an extrem case, a negative value of CRP indicates a lack of glide (e.g., cluster 10), that can reflect high swimming speed or novice behavior.
- c) between 56-62% of the cycle duration: this portion indicates the duration of the plateau related to the glide phase. Indeed, patterns associated with high swimming speeds are already close to anti-phase during this period, whereas patterns associated to low swimming speeds are still close to in-phase (i.e. gliding)

- d) end of the cycle [80-90 % of the cycle duration]: this portion informs about the nature of the coordination during the arm-leg recovery (i.e. arm extension and leg flexion). This portion should be close to anti-phase, at least should finish around -180°. This part allows to discriminate swimmers who extend their arms fast enough from swimmers who exhibit a delay in their arm extension.

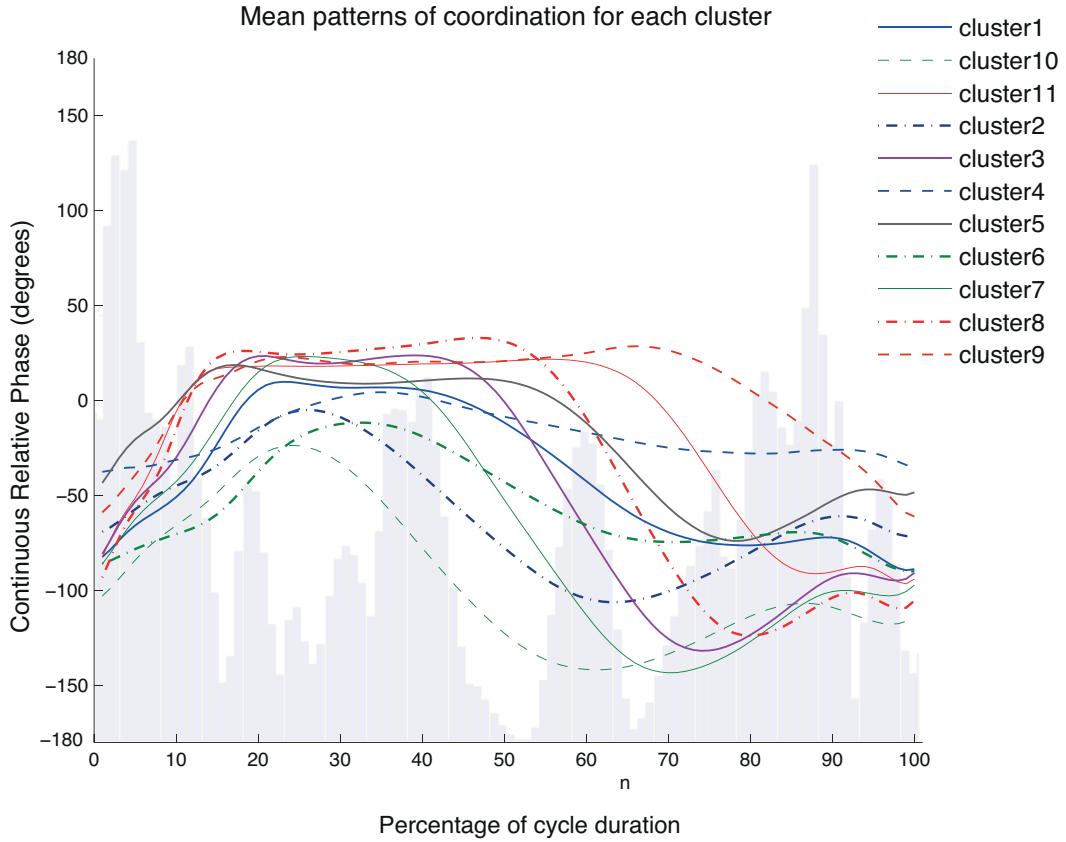


Figure 41. Patterns of coordination for the 11 clusters and sparsity for each value (in grey, from 1-100), computed by the Fisher-EM algorithm.

Pattern 1. The mean pattern of coordination of the cluster 1 is characterized by a plateau close to 0° of CRP, defining a glide phase with both arms and legs in maximal extension, and by a duration of glide with arms and legs outstretched of 0.41 ± 0.27 s (Figure 42). The mean value of the CRP at the beginning of the cycle was -82.51 ± 24.00 °, defining a partial superposition of the leg extension and the arm recovery (i.e. flexion). The mean duration of the time spent in in-phase mode (i.e. except the glide time that corresponds to an effective in-phase mode) was 23.83 ± 10.90 %. The mean CRP value at the end of the knee extension position was -51.51 ± 37.50 °, showing that elbows were not entirely flexed (i.e. had finished their propulsion) when the legs began their flexion (i.e. recovery).

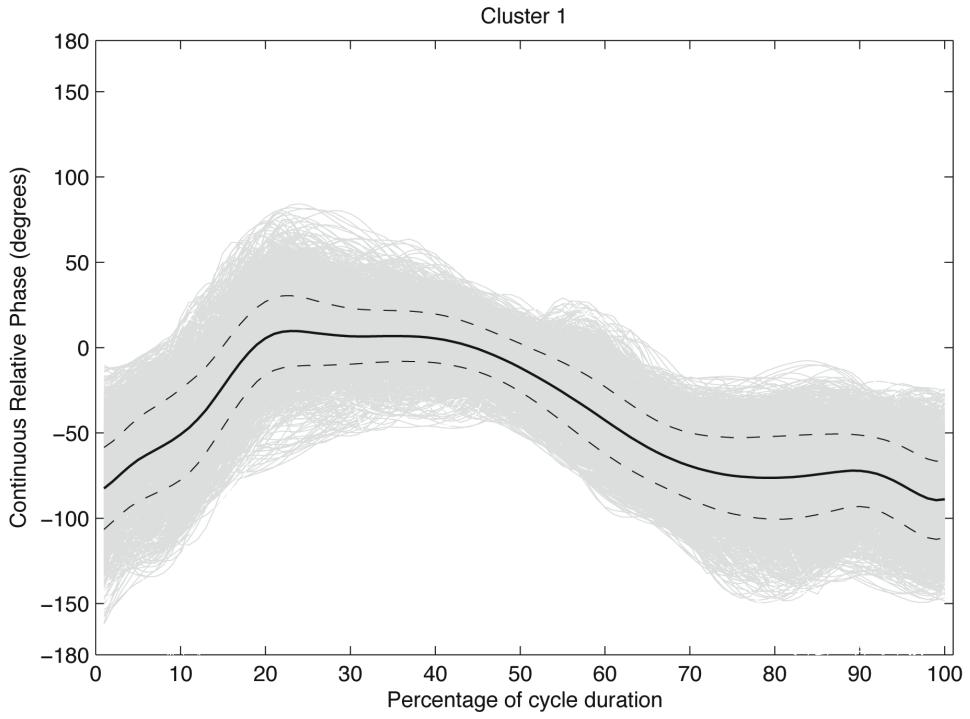


Figure 42. Mean pattern of coordination (black line), standard deviation (dotted line) and individual patterns (grey) of the cluster 1.

This pattern of coordination appeared during in all groups, but was more used by the analogy group, and less used by the pacer group (Table 8). Identically, this pattern appeared mostly used in high speed condition, mostly by the pacer, analogy and prescription groups.

Table 8. Distribution of the Pattern I through the different groups, speeds and instruction condition (free or constrained) (in % of total occurrence).

Cluster 1	Control Group		Analogy Group		Pacer Group		Prescription Group	
	Low speed	High speed	Free	Constrained	Free	Constrained	Free	Constrained
Presence in each group		8.31			13.59		7.52	11.72
Repartition between the groups		24.62			35.15		14.39	25.84
Speed condition	43	57	18	82	22	78	20	80
Instruction condition	22	78	22	78	19	81	19	81

Pattern 2. The mean pattern of coordination of the cluster 2 is characterized by the absence of a real plateau, but a maximal value of CRP close to 0° , defining a “glide position” (i.e. more precisely the position between leg propulsion and arm propulsion) with both arms and legs in maximal extension. This pattern was characterized by a short duration spent with arms and legs outstretched of 0.12 ± 0.10 s (Figure 43). The mean value of the CRP at the beginning of the cycle was $-69.17 \pm 28.38^\circ$, defining a parial superposition of the leg extension and the arm recovery (i.e. flexion). The mean duration of the time spent in in-phase mode (i.e. except the glide time that corresponds to an effective in-phase mode) was $15.67 \pm 10.65\%$. The mean CRP value at the end of the knee extension position was $-80.20 \pm 43.35^\circ$, showing that elbows were not entirely flexed (i.e. had finished their propulsion) when the legs began their flexion (i.e. recovery).

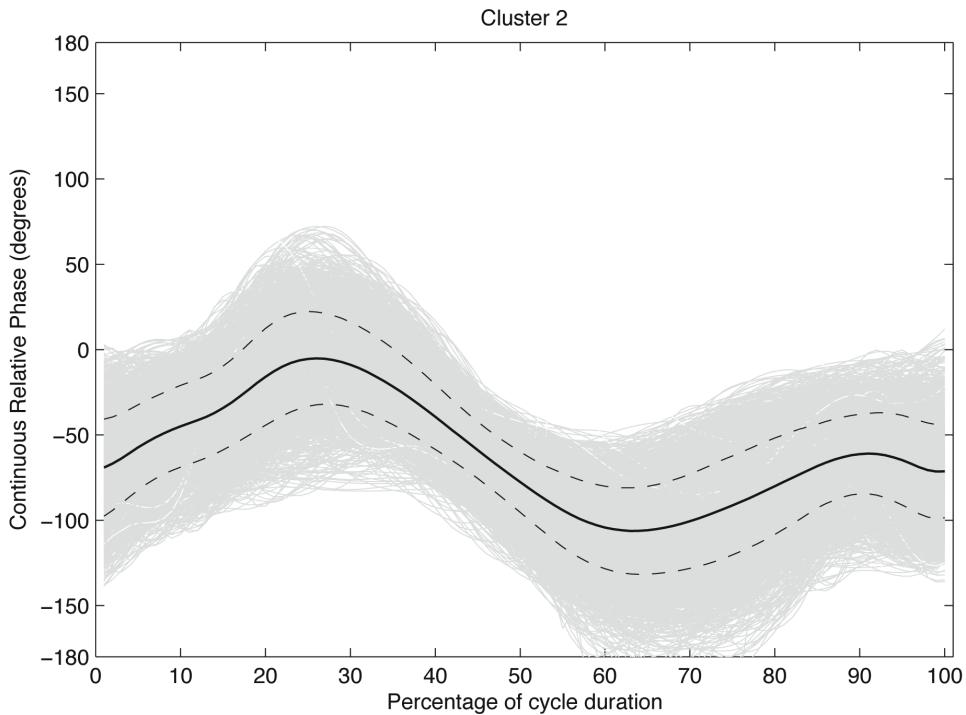


Figure 43. Mean pattern of coordination (black line), standard deviation (dotted line) and individual patterns (grey) of the cluster 2.

This pattern of coordination appeared used principally by the control group (approximatively 50%), whereas the analogy group seemed to avoid using this pattern (7,16% of this pattern was done by the analogy group) (Table 9). Interestingly, and to highlight this last point, this pattern was mostly used during the free trials rather than during the constrained trials (distribution between free-constrained practice was 38-62

%, whereas the normality is 20-80% considering the 2 trials freely performed and the 8 trials performed under an additional constraint): therefore the use of analogy limit the use of this pattern. Identically to the pattern 1, this pattern appeared mostly used in high swimming speed condition rather than in low swimming speed condition.

Table 9. Distribution of the Pattern 2 through the different groups, speeds and instruction condition (free or constrained) (in % of total occurrence).

Cluster 2	Control Group		Analogy Group		Pacer Group		Prescription Group	
	Low speed Free	High speed Constrained	Low speed Free	High speed Constrained	Low speed Free	High speed Constrained	Low speed Free	High speed Constrained
Presence in each group	13.59		2.33		12.65		6.19	
Repartition between the groups	47.85		7.16		28.77		16.22	
Speed condition	33	67	10	90	36	64	19	81
Instruction condition	20	80	38	62	25	75	21	79

Pattern 3. The mean pattern of coordination of the cluster 3 is characterized by a plateau close to 23° of CRP, defining a glide phase with the legs slightly flexed when the arms were outstretched (even if this position is still considered as in-phase). The duration of the glide with arms and legs outstretched was 0.52 ± 0.26 s (Figure 44). The mean value of the CRP at the beginning of the cycle was $-80.90 \pm 29.18^\circ$, defining a parial superposition of the leg extension and the arm recovery (identical to the pattern 1). The mean duration of the time spent in in-phase mode (i.e. except the glide time that corresponds to an effective in-phase mode) was 19.21 ± 8.51 %. The mean CRP value at the end of the knee extension position was $-91.91 \pm 56.37^\circ$, showing that elbows were not entirely flexed (i.e. had finished their propulsion) when the legs began their flexion (i.e. recovery).

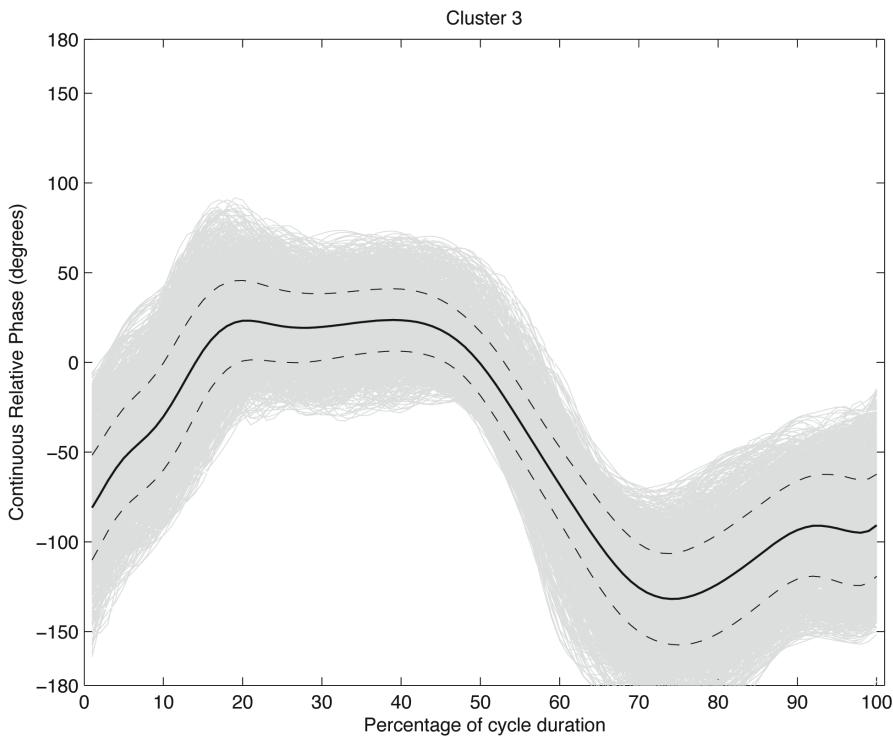


Figure 44. Mean pattern of coordination (black line), standard deviation (dotted line) and individual patterns (grey) of the cluster 3.

This pattern appeared used by every groups, but was preferably used by the analogy group and less used by the pacer group (Table 10). Identically, this pattern was preferably exhibited in high speed condition, except for the control group who used it in the same manner in high or low speed condition.

Table 10. Distribution of the Pattern 3 through the different groups, speeds and instruction condition (free or constrained) (in % of total occurrence).

Cluster 3	Control Group		Analogy Group		Pacer Group		Prescription Group	
	Low speed	High speed	Free	Constrained	Free	Constrained	Free	Constrained
Presence in each group	5.85		17.36		6.21		11.05	
Repartition between the groups	17.60		45.59		12.07		24.74	
Speed condition	50	50	31	69	29	71	38	62
Instruction condition	16	84	16	84	19	81	17	83

Pattern 4. The mean pattern of coordination of the cluster 4 is characterized by a plateau close to 0° of CRP, defining a glide phase with both arms and legs outstretched. The duration of the glide with arms and legs outstretched was 0.55 ± 0.48 s (Figure 45). The mean value of the CRP at the beginning of the cycle was -

$37.69 \pm 31.21^\circ$, the lowest of the 11 patterns, defining an important superposition of the leg extension and the arm recovery. The mean duration of the time spent in in-phase mode (i.e. except the glide time that corresponds to an effective in-phase mode) was $48.19 \pm 18.32\%$, the most important of the 11 patterns. The mean CRP value at the end of the knee extension position was $-19.38 \pm 30.72^\circ$, showing that elbows and knees were in an in-phase relationship, defining a knee flexion (i.e. recovery) occurring with a elbow flexion (i.e.; propulsion). In fact, this pattern corresponds to the « accordion » pattern, that is defined by a CRP close to 0° (in-phase mode) within the entire cycle (i.e. superposition of contradictory actions).

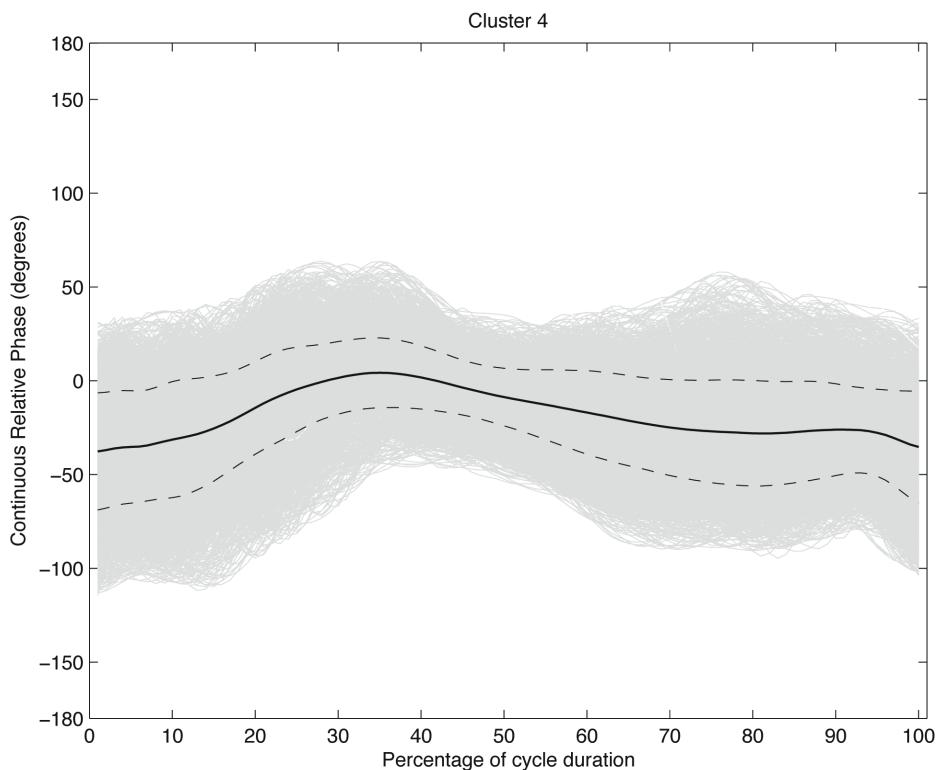


Figure 45. Mean pattern of coordination (black line), standard deviation (dotted line) and individual patterns (grey) of the cluster 4.

This pattern was used by every groups, but was predominantly exhibited by the control group, and rarely used by the analogy and pacer groups (who exhibited it essentially at low swimming speed) (Table 11).

Table 11. Distribution of the Pattern 4 through the different groups, speeds and instruction condition (free or constrained) (in % of total occurrence).

Cluster 4	Control Group		Analogy Group		Pacer Group		Prescription Group	
	Low speed	High speed	Low speed	High speed	Low speed	High speed	Low speed	High speed
	Free	Constrained	Free	Constrained	Free	Constrained	Free	Constrained
Presence in each group	24.77		2.13		6.88		12.65	
Repartition between the groups	61.18		4.59		10.98		23.26	
Speed condition	52	48	77	23	74	26	40	60
Instruction condition	22	78	28	72	19	81	23	77

Pattern 5. The mean pattern of coordination of the cluster 5 is characterized by a long plateau close to 6° of CRP, defining a glide phase with both arms and legs in maximal extension, and by a duration of glide with arms and legs outstretched of 0.70 ± 0.33 s (Figure 46). The mean value of the CRP at the beginning of the cycle was $-43.52 \pm 26.89^\circ$, defining a parial superposition of the leg extension and the arm recovery (i.e. flexion). The mean duration of the time spent in in-phase mode (i.e. except the glide time that corresponds to an effective in-phase mode) was $30.90 \pm 11.41\%$. The mean CRP value at the end of the knee extension position was $-52.73 \pm 40.58^\circ$, showing again that elbows were not entirely flexed (i.e. had finished their propulsion) when the legs began their flexion (i.e. recovery).

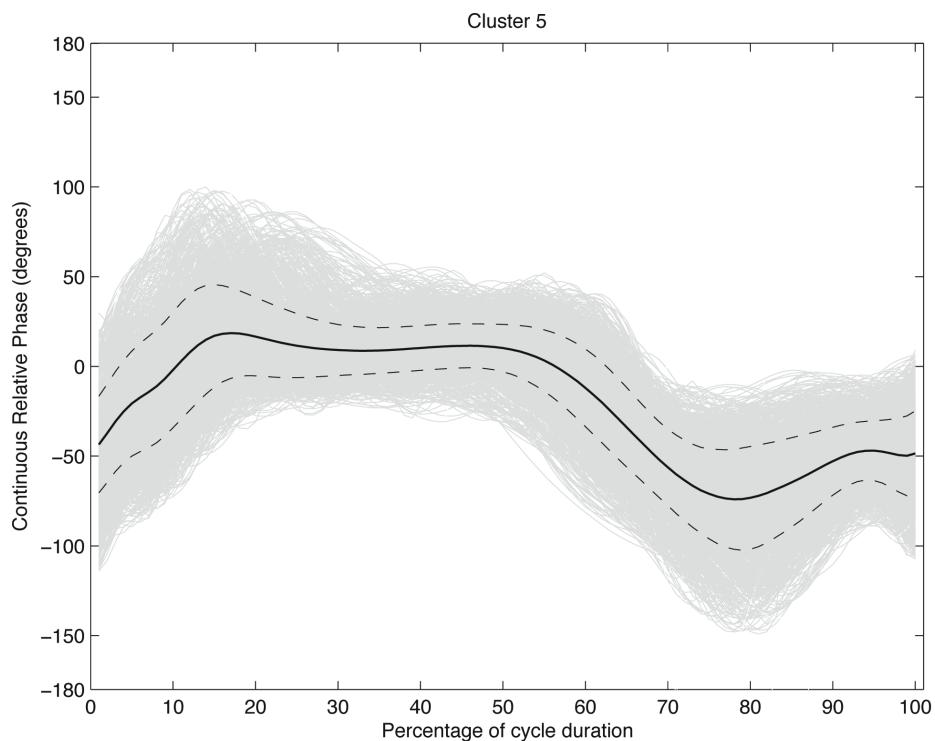


Figure 46. Mean pattern of coordination (black line), standard deviation (dotted line) and individual patterns (grey) of the cluster 5.

This pattern of coordination was exhibited by every groups, except maybe by the analogy group where this pattern represented less than 1% of the patterns used. Conversely, the use of a prescription seems to favor this pattern (Table 12). This pattern appeared preferable in low swimming speed condition than in high swimming speed condition (i.e. explaining the relative long period spent with arms and legs outstretched).

Table 12. Distribution of the Pattern 5 through the different groups, speeds and instruction condition (free or constrained) (in % of total occurrence).

Cluster 5	Control Group		Analogy Group		Pacer Group		Prescription Group	
	Low speed	High speed	Free	Constrained	Free	Constrained	Free	Constrained
Presence in each group	7.70		7.90		0.77		15.73	
Repartition between the groups	28.73		25.73		1.86		43.69	
Speed condition	61	39	68	32	85	15	50	50
Instruction condition	21	79	19	81	31	69	20	80

Pattern 6. The mean pattern of coordination of the cluster 6 is characterized by the absence of a real plateau, even if the maximal value of CRP is close to 0°, defining a position with both arms and legs in maximal extension. The duration of glide with arms and legs outstretched was 0.20 ± 0.18 s, close to the minimal duration exhibited by cluster 2 (Figure 47). The mean value of the CRP at the beginning of the cycle was -85.87 ± 28.17 °, defining a partial superposition of the leg extension and the arm recovery (close to the CRP exhibited by cluster 1 and 3). The mean duration of the time spent in in-phase mode (i.e. except the glide time that corresponds to an effective in-phase mode) was 15.31 ± 10.96 %. The mean CRP value at the end of the knee extension position was -51.19 ± 36.45 °, showing again that elbows were not entirely flexed (i.e. had finished their propulsion) when the legs began their flexion (i.e. recovery).

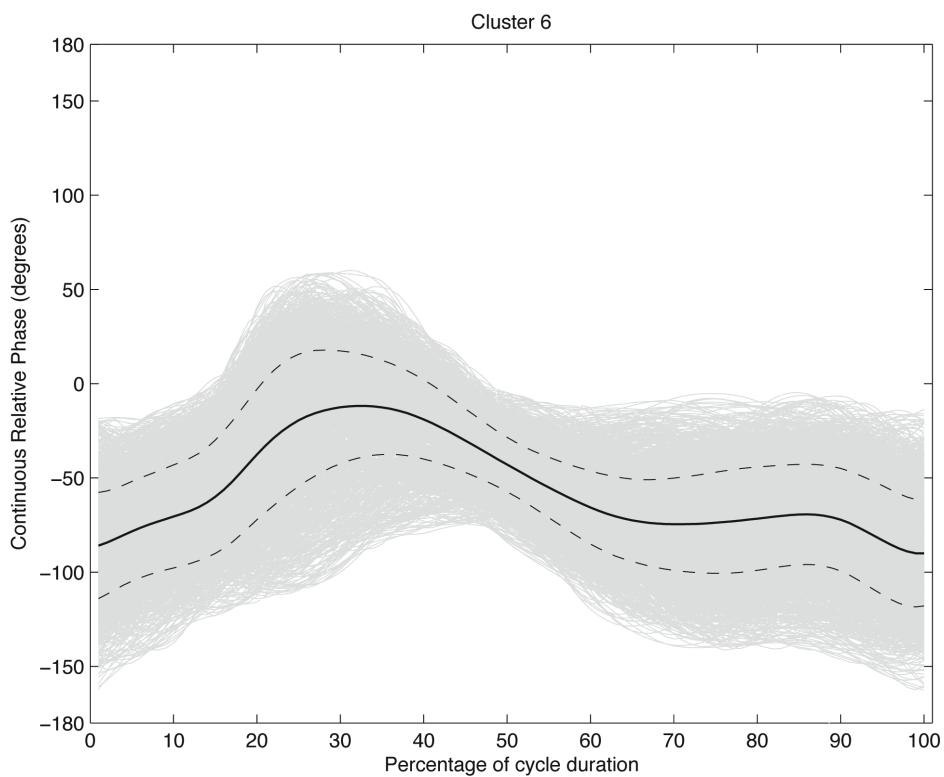


Figure 47. Mean pattern of coordination (black line), standard deviation (dotted line) and individual patterns (grey) of the cluster 6.

This pattern of coordination was observed in every groups, but was preferably exhibited by the control group and less exhibited by the analogy and prescription groups (Table 13). In addition, this pattern of coordination appeared more used in high swimming speed condition than in low swimming speed condition (i.e. explaining the absence of glide time).

Table 13. Distribution of the Pattern 6 through the different groups, speeds and instruction condition (free or constrained) (in % of total occurrence).

Cluster 6	Control Group		Analogy Group		Pacer Group		Prescription Group	
	Low speed	High speed	Free	Constrained	Free	Constrained	Free	Constrained
Presence in each group	13.14				5.68		11.01	
Repartition between the groups	44.25				16.70		23.95	
Speed condition	37	63	5	95	26	74	14	86
Instruction condition	20	80	26	74	22	78	19	81

Pattern 7. The mean pattern of coordination of the cluster 7 is characterized by a plateau close to 15° of CRP, defining a glide phase with the legs slightly flexed when

the arms were outstretched (even if this position is still considered as in-phase). The duration of the glide with arms and legs outstretched was 0.33 ± 0.21 s (Figure 48). The mean value of the CRP at the beginning of the cycle was $-86.26 \pm 27.93^\circ$, defining a parial superposition of the leg extension and the arm recovery. The mean duration of the time spent in in-phase mode (i.e. except the glide time that corresponds to an effective in-phase mode) was $16.59 \pm 8.23\%$. The mean CRP value at the end of the knee extension position was $-100.68 \pm 60.45^\circ$, close to the minimum value observed in all patterns. This low value shows the ability to maintain a certain knee extension until the end of the elbow flexion (i.e. swimmers exhibiting this pattern were able to delay their leg recovery).

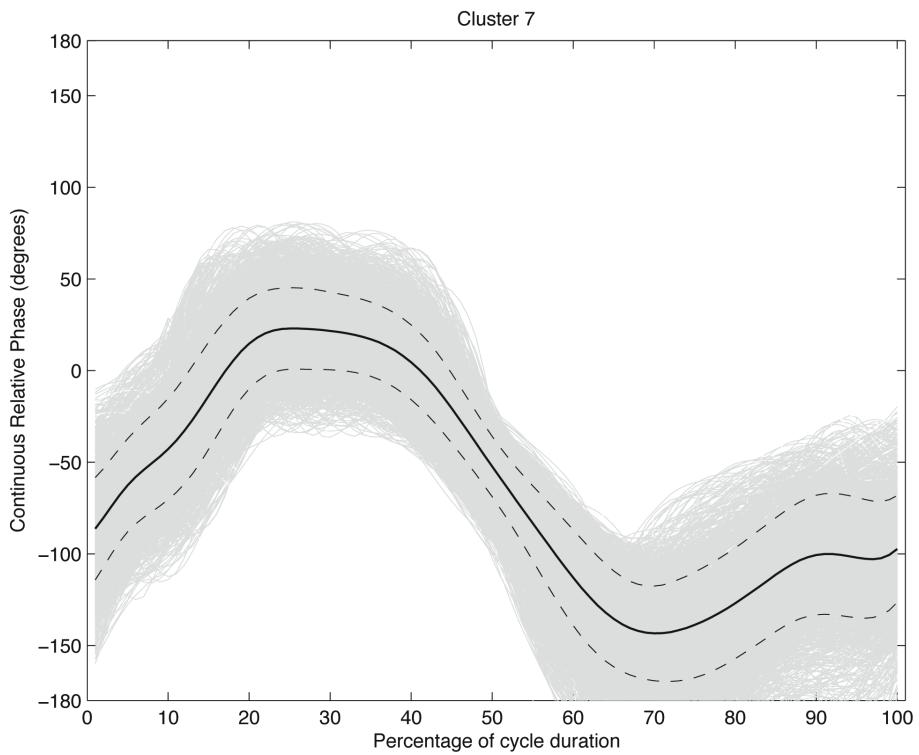


Figure 48. Mean pattern of coordination (black line), standard deviation (dotted line) and individual patterns (grey) of the cluster 7.

This pattern appeared preferably used by the analogy group (Table 14). In all groups, this pattern was mostly exhibited in high swimming speed condition.

Table 14. Distribution of the Pattern 7 through the different groups, speeds and instruction condition (free or constrained) (in % of total occurrence).

Cluster 7	Control Group		Analogy Group		Pacer Group		Prescription Group	
	Low speed	High speed	Low speed	High speed	Low speed	High speed	Low speed	High speed
	Free	Constrained	Free	Constrained	Free	Constrained	Free	Constrained
Presence in each group	6.00		11.60		6.93		7.18	
Repartition between the groups	23.12		39.03		17.25		20.60	
Speed condition	41	59	16	84	29	71	27	73
Instruction condition	21	79	25	75	21	79	16	84

Pattern 8. The mean pattern of coordination of the cluster 8 is characterized by a plateau close to 25° of CRP, defining a glide phase with the legs slightly flexed when the arms were outstretched. The duration of the glide with arms and legs outstretched was 0.82 ± 0.33 s (Figure 49). The mean value of the CRP at the beginning of the cycle was $-93.21 \pm 23.49^\circ$, defining a parial superposition of the leg extension and the arm recovery, but this superposition was lower than in the other previous patterns. The mean duration of the time spent in in-phase mode (i.e. except the glide time that corresponds to an effective in-phase mode) was $18.79 \pm 8.45\%$. The mean CRP value at the end of the knee extension position was $-69.40 \pm 61.79^\circ$, showing that elbows were not entirely flexed (i.e. had finished their propulsion) when the legs began their flexion (i.e. recovery).

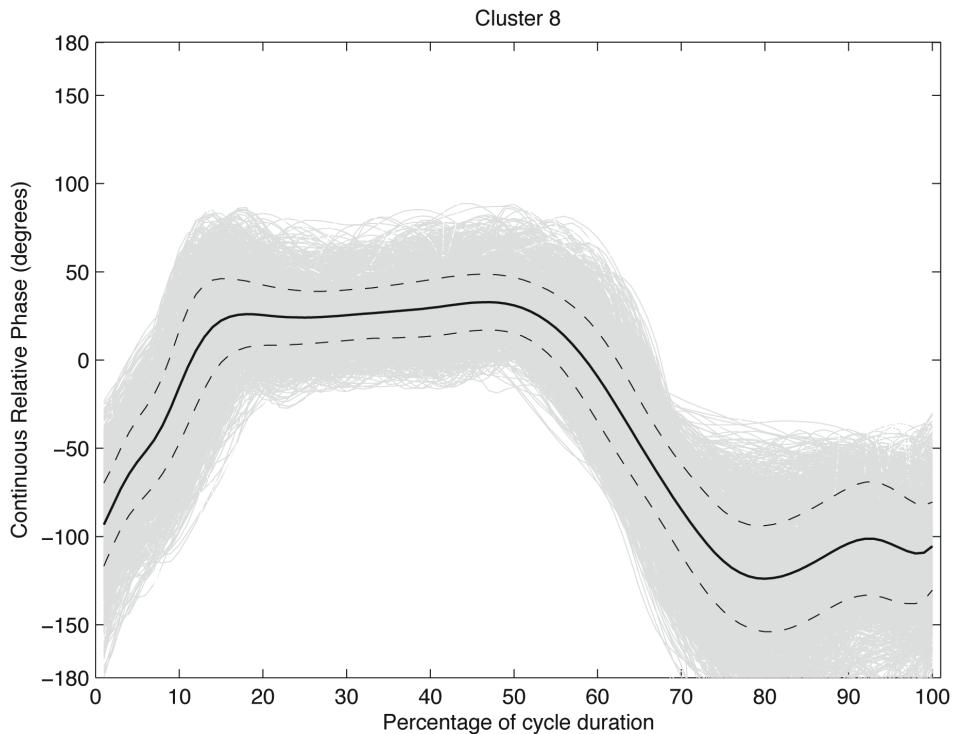


Figure 49. Mean pattern of coordination (black line), standard deviation (dotted line) and individual patterns (grey) of the cluster 8.

This pattern of coordination was used by all groups, but appeared preferably used by the analogy group (Table 15). This pattern appeared mostly exhibited by the analogy in low swimming speed condition, whereas no difference in terms of swimming speed appeared for the other groups.

Table 15. Distribution of the Pattern 8 through the different groups, speeds and instruction condition (free or constrained) (in % of total occurrence).

Cluster 8	Control Group		Analogy Group		Pacer Group		Prescription Group	
	Low speed Free	High speed Constrained	Low speed Free	High speed Constrained	Low speed Free	High speed Constrained	Low speed Free	High speed Constrained
Presence in each group	5.29		16.88		8.53		8.21	
Repartition between the groups	16.72		46.56		17.41		19.31	
Speed condition	74	26	80	20	57	43	44	56
Instruction condition	21	79	16	84	22	78	23	77

Pattern 9. The mean pattern of coordination of the cluster 9 is characterized by a plateau close to 20° of CRP, defining a glide phase with the legs slightly flexed when the arms were outstretched. The duration of the glide with arms and legs outstretched was 0.98 ± 0.67 s (Figure 50). The mean value of the CRP at the beginning of the cycle was $-59.03 \pm 24.55^\circ$, defining an important parial superposition of the leg extension and the arm recovery. The mean duration of the time spent in in-phase mode (i.e. except the glide time that corresponds to an effective in-phase mode) was 35.31 ± 14.98 % (only the pattern 4 showed more in-phase coordination during the cycle). The mean CRP value at the end of the knee extension position was $4.64 \pm 36.89^\circ$, showing that the flexion of the elbows started at the same time as the flexion of the knees.

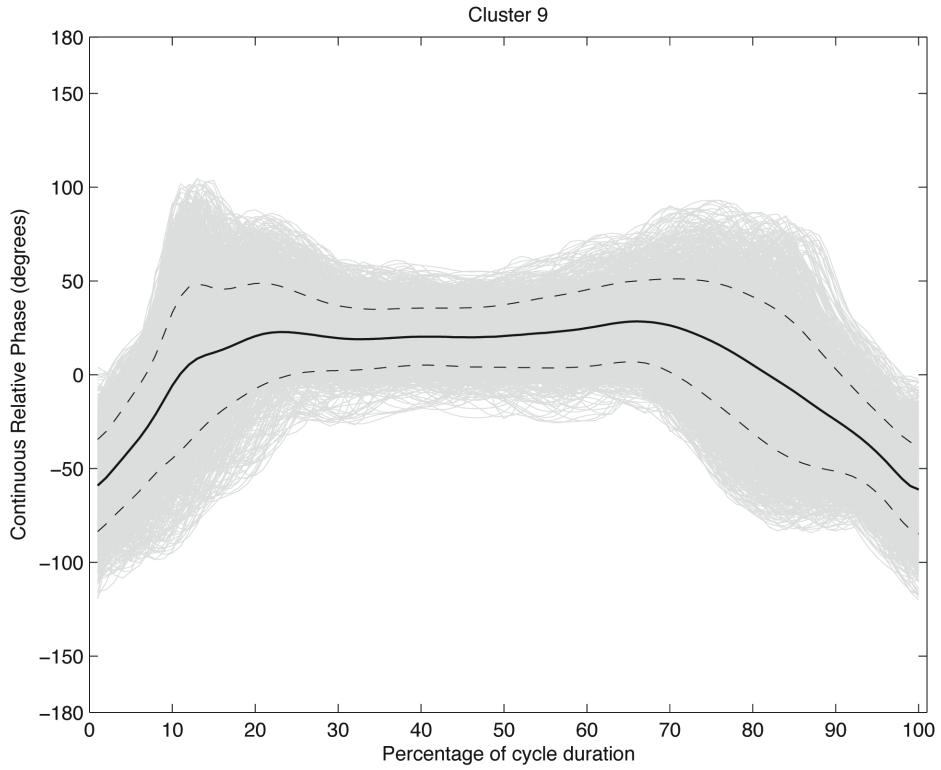


Figure 50. Mean pattern of coordination (black line), standard deviation (dotted line) and individual patterns (grey) of the cluster 9.

This pattern of coordination was exhibited by all groups, but the use of the analogy and to a lesser extent of the prescription seemed to favor its use (Table 16). In addition, this pattern was more used in low swimming speed condition.

Table 16. Distribution of the Pattern 9 through the different groups, speeds and instruction condition (free or constrained) (in % of total occurrence).

Cluster 9	Control Group		Analogy Group		Pacer Group		Prescription Group	
	Low speed Free	High speed Constrained	Low speed Free	High speed Constrained	Low speed Free	High speed Constrained	Low speed Free	High speed Constrained
Presence in each group	3.32		10.85		6.31		7.70	
Repartition between the groups	14.69		41.91		18.04		25.36	
Speed condition	81	19	50	50	83	17	91	9
Instruction condition	21	79	23	77	26	74	22	78

Pattern 10. The mean pattern of coordination of the cluster 10 is characterized by the absence of a real plateau, and by a maximal value of CRP close to -25° . This first value indicates an absence of a fully streamlined position (i.e. with arms and legs outstretched). This lack of glide was corroborated by a small time spent with arms and

legs outstretched: 0.07 ± 0.12 s (the lowest value of all groups) (Figure 51). More precisely, the two oscillators did not really meet in fully extended position; namely that as well as the knees had finished their extension, the elbows started their flexion. The mean value of the CRP at the beginning of the cycle was $-103.01 \pm 27.16^\circ$, defining a parial superposition of the leg extension and the arm recovery, but this pattern was the one that indicated the less superposition (i.e. the value of CRP at the beginning of the cycle was the closest to anti-phase in all groups). The mean duration of the time spent in in-phase mode (i.e. except the glide time that corresponds to an effective in-phase mode) was $8.22 \pm 12.48\%$. The mean CRP value at the end of the knee extension position was $-109.17 \pm 49.58^\circ$, showing again that elbows were not entirely flexed when the legs began their flexion, but this pattern was the one that showed the CRP at the end of the knee extension position the closest to anti-phase (i.e. the hydrodynamical position of the leg maintained during the elbow flexion).

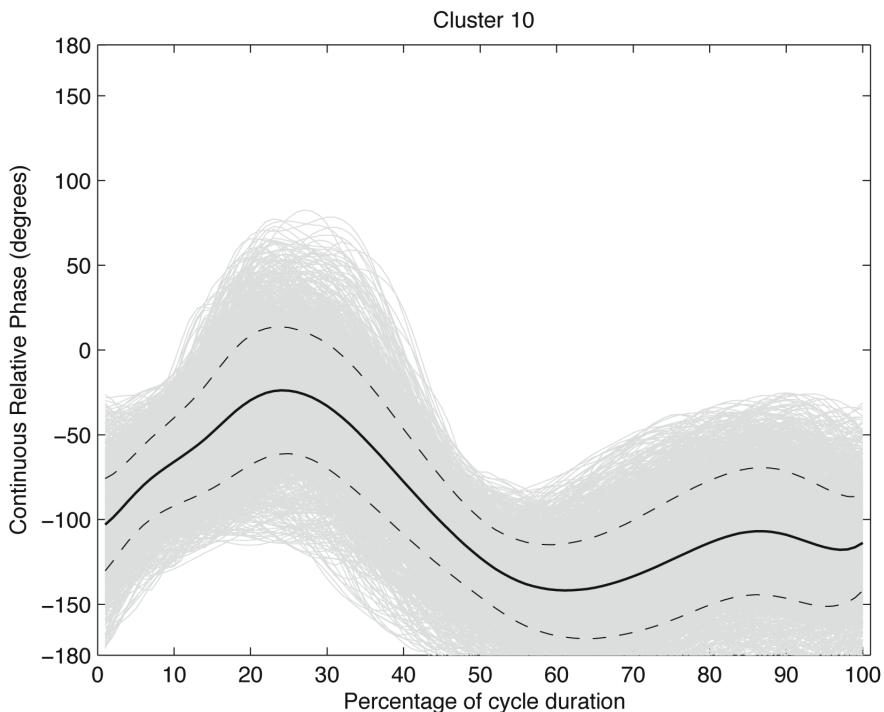


Figure 51. Mean pattern of coordination (black line), standard deviation (dotted line) and individual patterns (grey) of the cluster 10.

This pattern was less used by the analogy and prescription groups, whereas the use of a pacer seemed to increase the presence of this pattern (Table 17). This pattern was principally used in high swimming speed condition, explaining the lack of glide phase. Only the pacer group appeared as using this pattern in both speed conditions.

Table 17. Distribution of the Pattern 10 through the different groups, speeds and instruction condition (free or constrained) (in % of total occurrence).

Cluster 10	Control Group		Analogy Group		Pacer Group		Prescription Group	
	Low speed	High speed	Free	Constrained	Free	Constrained	Free	Constrained
Presence in each group	5.30		1.30		18.99		0.48	
Repartition between the groups	27.81		5.95		64.36		1.87	
Speed condition	23	77	26	74	44	56	24	76
Instruction condition	26	74	58	42	28	72	9	91

Pattern 11. The mean pattern of coordination of the cluster 11 is characterized by a plateau close to 10° of CRP, defining a small flexion of the legs during the glide phase, and by a duration of glide with arms and legs outstretched of 1.14 ± 0.50 s (Figure 52). The mean value of the CRP at the beginning of the cycle was -82.49 ± 25.45 °, defining a parial superposition of the leg extension and the arm recovery (i.e. flexion). The mean duration of the time spent in in-phase mode (i.e. except the glide time that corresponds to an effective in-phase mode) was 26.09 ± 12.48 %. The mean CRP value at the end of the knee extension position was -40.05 ± 53.49 °, showing that elbows were not entirely flexed (i.e. had finished their propulsion) when the legs began their flexion (i.e. recovery).

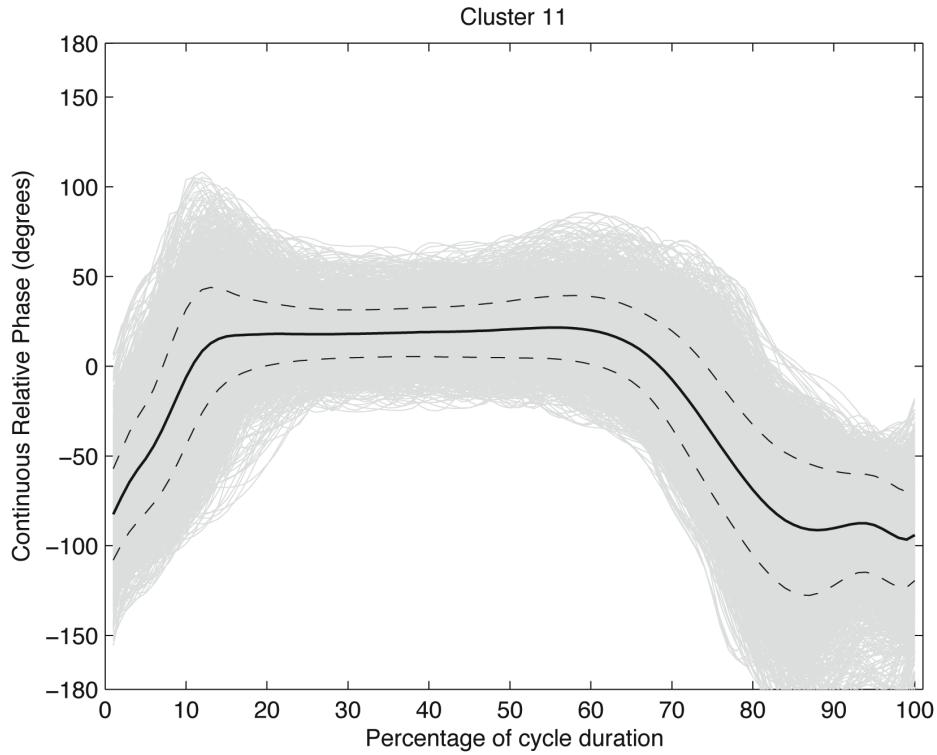


Figure 52. Mean pattern of coordination (black line), standard deviation (dotted line) and individual patterns (grey) of the cluster 11.

This pattern appeared used in same proportions by all groups (Table 18). However, it was more used in low swimming speed condition than in high swimming speed condition.

Table 18. Distribution of the Pattern 11 through the different groups, speeds and instruction condition (free or constrained) (in % of total occurrence).

Cluster 11	Control Group		Analogy Group		Pacer Group		Prescription Group	
	Low speed	High speed	Free	Constrained	Free	Constrained	Free	Constrained
Presence in each group	6.73		10.37		14.10		13.01	
Repartition between the groups	19.46		26.18		26.34		28.01	
Speed condition	75	25	90	10	73	27	89	11
Instruction condition	18	82	20	80	17	83	22	78

Use of coordination pattern and stability regimes. Tables 19, 20, 21 and 22 present the stability regimes (i.e. defined by the mean switching ratio and the mean occurrence of pattern within each session) exhibited by the learners during each session. Few learners exhibited a stable pattern during the first session (5 out of 26), but all passed through a metastable regime during the learning process. In addition, although all participants did not show stability during the last session, they all passed through a stable regime during one or more sessions (except two participants in low swimming speed condition). Only two participants really showed a multi-stable regime during at least one session (participant 7 from pacer group and 6 from prescription group in low swimming speed condition). However, individual data presenting trial per trial stability regimes (in appendices) showed that learners exhibited different stability regimes within a session (i.e. between trials, Figure 53). Thus, although the entire session was not always defined as stable at the end of the learning process, all learners increased the number of stable trials with learning, after being passed through metastable trials.

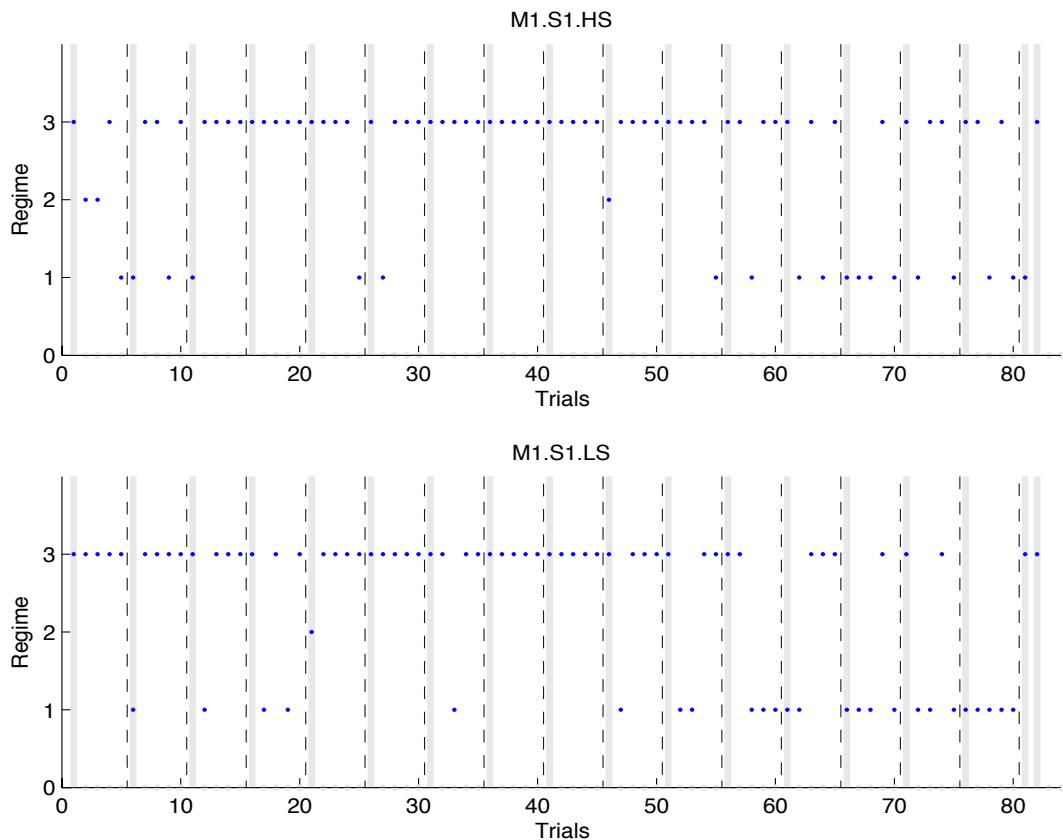


Figure 53. Stability regimes (1 = stable ; 2 = multi-stable ; 3 = metastable) trial after trial in high speed condition (top) and low speed condition (bottom). In grey background, free trials whereas the background of constrained trials is white.

Tables 23, 24 and 25 synthesize the patterns respectively exhibited in pre-, post- and re-test as well as the total number of patterns exhibited during all the learning process and among them the total number patterns that have been stabilized during at least one trial.

Table 19. Stability regimes (1 = stable ; 2 = multi-stable ; 3 = metastable) during each session for each participant of the control and analogy groups in low swimming speed condition.

Control Group at low swimming speed							
Session	Participants						
	1	2	4	5	6	7	8
1	3	3	3	3	3	3	3
2	3	3	3	3	3	3	1
3	3	1	3	3	3	3	1
4	3	3	3	3	3	1	3
5	3	3	3	3	3	3	3
6	3	3	3	3	3	3	3
7	3	3	3	3	3	3	3
8	3	3	3	3	3	3	3
9	3	3	3	3	3	1	3
10	3	3	3	3	3	1	3
11	3	3	1	3	3	3	3
12	1	3	3	3	3	3	3
13	3	3	3	3	3	1	3
14	1	1	3	3	3	1	3
15	1	1	3	3	3	1	3
16	1	1	3	1	3	1	3

Analogy Group at low swimming speed							
Session	Participants						
	1	2	3	4	6	7	8
1	1	3	3	3	3	3	3
2	3	3	3	3	3	3	1
3	1	3	1	3	3	3	3
4	1	3	3	3	3	3	3
5	1	3	3	3	1	3	3
6	1	3	3	1	3	3	1
7	1	3	3	3	3	3	3
8	1	3	1	3	1	3	3
9	1	3	3	3	1	3	1
10	3	3	3	3	1	3	1
11	1	3	3	3	1	3	1
12	3	3	3	3	1	1	1
13	1	3	3	3	1	3	3
14	1	3	3	3	3	3	3
15	3	3	1	3	1	3	3
16	1	3	3	3	3	3	3

Table 20. Stability regimes (1 = stable ; 2 = multi-stable ; 3 = metastable) during each session for each participant of the pacer and prescription groups in low swimming speed condition.

Pacer Group at low swimming speed

Session	Participants					
	1	3	5	6	7	8
1	3	3	3	1	3	3
2	1	3	1	3	3	3
3	3	3	3	3	3	3
4	3	3	3	3	3	3
5	3	1	3	3	3	3
6	3	3	1	3	3	3
7	3	3	1	3	3	3
8	3	3	1	3	3	1
9	3	3	3	3	3	1
10	3	3	3	3	1	3
11	3	1	3	3	3	3
12	3	3	3	3	1	3
13	3	3	3	3	1	3
14	3	3	3	3	1	3
15	1	3	3	3	1	3
16	3	3	1	3	1	3

Prescription Group at low swimming speed

Session	Participants					
	2	4	5	6	7	8
1	3	3	3	3	3	3
2	3	3	3	3	3	3
3	3	3	3	3	3	3
4	3	3	3	3	3	3
5	3	3	3	1	3	3
6	3	3	1	3	3	3
7	3	3	1	3	3	3
8	3	3	3	3	3	3
9	3	3	3	2	3	1
10	3	3	1	3	3	3
11	3	3	1	3	3	3
12	1	3	1	3	3	3
13	3	1	1	3	3	3
14	3	1	1	3	3	3
15	3	1	1	3	3	3
16	3	1	1	3	3	3

Table 21. Stability regimes (1 = stable ; 2 = multi-stable ; 3 = metastable) during each session for each participant of the control and analogy groups in high swimming speed condition.

Control Group at high swimming speed							
Session	Participants						
	1	2	4	5	6	7	8
1	3	1	3	1	3	1	3
2	3	1	1	3	3	1	3
3	3	1	3	3	1	1	1
4	3	3	3	3	3	1	3
5	3	3	1	1	3	1	3
6	3	1	3	3	3	1	3
7	3	3	3	3	1	1	3
8	3	3	1	3	3	1	3
9	3	3	3	3	3	1	3
10	3	3	3	3	3	1	3
11	3	3	3	3	3	3	1
12	3	3	1	1	3	3	1
13	3	3	3	3	3	3	3
14	1	3	3	3	3	1	3
15	1	1	1	1	3	1	3
16	3	3	3	3	3	1	3

Analogy Group at high swimming speed							
Session	Participants						
	1	2	3	4	6	7	8
1	1	3	3	3	3	3	3
2	3	3	1	3	3	3	3
3	1	3	3	3	3	3	3
4	1	3	3	3	3	3	3
5	1	3	3	3	3	3	3
6	1	1	3	3	3	3	3
7	1	3	3	3	3	3	3
8	1	3	3	3	3	1	3
9	3	1	3	3	3	3	3
10	3	3	3	3	3	3	3
11	1	1	3	3	3	3	3
12	3	3	3	1	3	3	3
13	1	1	3	1	3	3	3
14	1	1	3	3	3	3	3
15	1	3	3	3	3	3	3
16	1	3	3	3	3	3	3

Table 22. Stability regimes (1 = stable ; 2 = multi-stable ; 3 = metastable) during each session for each participant of the pace and prescription groups in high swimming speed condition.

Pacer Group at high swimming speed

Session	Participants					
	1	3	5	6	7	8
1	3	3	3	1	3	3
2	3	1	3	3	3	3
3	3	3	3	1	1	1
4	3	3	3	3	3	3
5	1	3	3	3	3	3
6	3	3	3	3	2	1
7	3	3	3	3	3	3
8	1	3	3	3	3	1
9	1	3	3	3	3	1
10	3	1	3	3	3	3
11	3	3	1	3	2	3
12	3	3	3	3	1	3
13	3	3	3	3	1	3
14	3	3	3	3	3	3
15	3	3	3	3	3	3
16	3	3	3	3	3	3

Prescription Group at high swimming speed

Session	Participants					
	2	4	5	6	7	8
1	3	3	3	3	3	3
2	3	3	3	3	3	3
3	3	3	3	3	3	3
4	3	3	3	3	3	3
5	3	3	3	3	3	3
6	3	3	3	3	3	3
7	3	3	3	3	3	3
8	3	3	3	3	3	3
9	3	3	3	3	3	3
10	3	3	3	3	3	3
11	1	3	3	3	3	3
12	3	3	3	1	3	3
13	3	3	3	3	3	3
14	3	1	3	3	3	3
15	3	3	1	3	1	3
16	3	3	1	1	1	3

Table 23. Coordination patterns exhibited by learners during pre-, post- and re-test in high swimming speed condition (top) and low swimming speed condition (bottom) (in grey the patterns that were stabilized).

Low swimming speed										High swimming speed																	
Group	Initial Pattern(s) (pre-test)									Final Pattern(s) (post-test)									Final Pattern(s) (re-test)								
	Participants				Participants					Participants				Participants					Participants								
Control	1,2,4, 6,7	1,2,6 /	2,10 1,4,6	2,6,10 2,4,6,	4 /	2,4,6 1,2,3, 4,6,7	11 9	11 11	/	3,5,8 1,5,9, 1,11	11 8,11	4 /	4,9,11 3,8 9,11	11 8 11	1,11,9 2,3,7	11 /	5,8 4	4,5	1,4,5								
Analogy	9,11 1,4,5	1,3,6, 7	2,4,6, 9	/	10 2,7	1,2,3, 4,6,7	9	11	/	3,8 1,10,1	3,5,8 1,10,1	8 1	8 11	11 10	/	3,7,8 /	9 9	4,9 11	1,11								
Pacer	1,2,4, 6,7	/	2,7 /	1,6,11 1,4,9	6,7,10 6,10	2,10 /	1,10,1 1	1,10,1 1	/	9,11 11	4,9 /	11 11	1,2,7 4,9 7	11 4,9 7	1,11,9 1,11,9	11 11	1,4,5 1,4,5	3,7 9	3,7 9								
Prescription	/	1,2,4, 6,7	/	1,2,5, 6,7	11 6,7	1,4,6 /	4,9 /	4,9 11	/	11 9,11	7 7	4,9 11	1,2,7 4,9 7	11 9	/	1,11,9 1,11,9	11 11	1,4,5 1,4,5	3,7 9								

Table 24. Number of different patterns visited during the 16 sessions (left) and among them number of patterns stabilized at least during one trial (right), in the low swimming speed condition.

Low swimming speed																		
Group	Number of visited Patterns								Number of stabilized Patterns									
	Participants							Mean	Participants						Mean			
	1	2	3	4	5	6	7		1	2	3	4	5	6				
Control	10	11	/	10	11	11	4	9	9	6	5	/	5	7	4	2	3	5
Analogy	3	7	9	11	/	7	9	10	8	2	4	4	2	/	2	3	2	3
Pacer	8	/	11	/	9	7	9	11	9	4	/	2	/	2	3	2	3	3
Prescription	/	9	/	10	7	10	11	11	10	/	2	/	2	2	3	2	3	2

Table 25. Number of different patterns visited during the 16 sessions (left) and among them number of patterns stabilized at least during one trial (right), in the high swimming speed condition.

High swimming speed																		
Group	Number of visited Patterns								Number of stabilized Patterns									
	Participants							Mean	Participants						Mean			
	1	2	3	4	5	6	7		1	2	3	4	5	6				
Control	11	10	/	9	9	11	4	8	9	5	7	/	3	3	3	2	2	4
Analogy	4	8	9	11	/	8	8	10	8	1	3	4	3	/	2	3	3	3
Pacer	3	/	9	/	10	7	8	9	8	2	/	4	/	4	3	4	1	3
Prescription	/	9	/	10	8	10	11	11	10	/	3	/	3	3	3	3	4	3

Switching ratio. During the constrained trials when learners had to follow an additional constraint, a three-way ANOVA revealed a session effect ($F(11.71,1171.61) = 2.98, p < .001, \eta_P^2 = .029, \varepsilon = .781$), a speed effect ($F(1,100) = 4.85, p = .030, \eta_P^2 = .046$) but also a significant triple interaction speed \times session \times group ($F(45,1500) = 2.43, p < .001, \eta_P^2 = .068$). Then, Bonferroni post-hoc tests showed that there was no difference between session 1 (pre-test) and session 16 (post-test), independently of the group and the speed condition. Moreover, no significant difference appeared between the four groups during session 1 and session 16. In fact, the significant interaction effect was essentially due to fluctuations sessions after sessions during the learning process. These fluctuations, observed in each group, were responsible to the significant differences showed between speeds, groups and sessions, but without defining any group/speed specificity.

A four-way ANOVA focusing essentially on the practice condition effect (free vs. constrained) on the switching ratio showed a significant interaction effect practice condition x group ($F(1,22) = 8.42, p = .008, \eta_p^2 = .277$). Thus, the analogy, pacer and prescription groups showed a higher switching ratio during the constrained trials ($M = 0.382 \pm 0.025$) than during the free trials ($M = 0.343 \pm 0.019$). Conversely, no difference were found for the control group (i.e. no difference between trials 1-2 and trials 3-10).

Exploration/exploitation ratio. A Kruskal-Wallis test computed on the exploration/exploitation ratio showed a significant effect of the group ($Z = 8.88, p = .031$) (Table 26). Thereafter, pairwise comparisons (Mann-Whitney tests) showed that the prescription group exhibited a higher ratio than the control group ($U = 39.00, p = .008$) and than the pacer group ($U = 32.00, p = .026$). This result suggested that the prescription group had a higher tendency to explore (i.e. to switch the pattern between cycle t and cycle $t+1$). No other difference was found between the groups (all $p_s > .128$).

Table 26. Exploration/exploitation ratio for each participant of the four groups.

Group	Participant								Mean
	1	2	3	4	5	6	7	8	
Control	0.731	0.678	/	0.652	0.812	1.015	0.231	0.821	0.773
Analogy	0.135	0.952	1.084	1.204	/	0.787	1.477	0.892	0.933
Pacer	0.710	/	0.949	/	0.937	0.815	0.705	0.914	0.838
Prescription	/	1.121	/	1.084	0.760	1.050	1.570	1.239	1.104

3-D histograms illustrate this exploration/exploitation ratio for each group through the number of occurrence of the 121 potential transitions (Figures 54, 55, 56 et 57). The diagonal represents a succession of identical patterns (i.e. exploitation), when the succession of different patterns are represented by the left and right side of the diagonal. For instance, previous results are shown again here by the strong presence of the pattern 4 in the control group, and with a strong exploitation of this pattern during the learning process (i.e. twice the maximal exploitation observed in the other groups). Individual data are available in appendices.

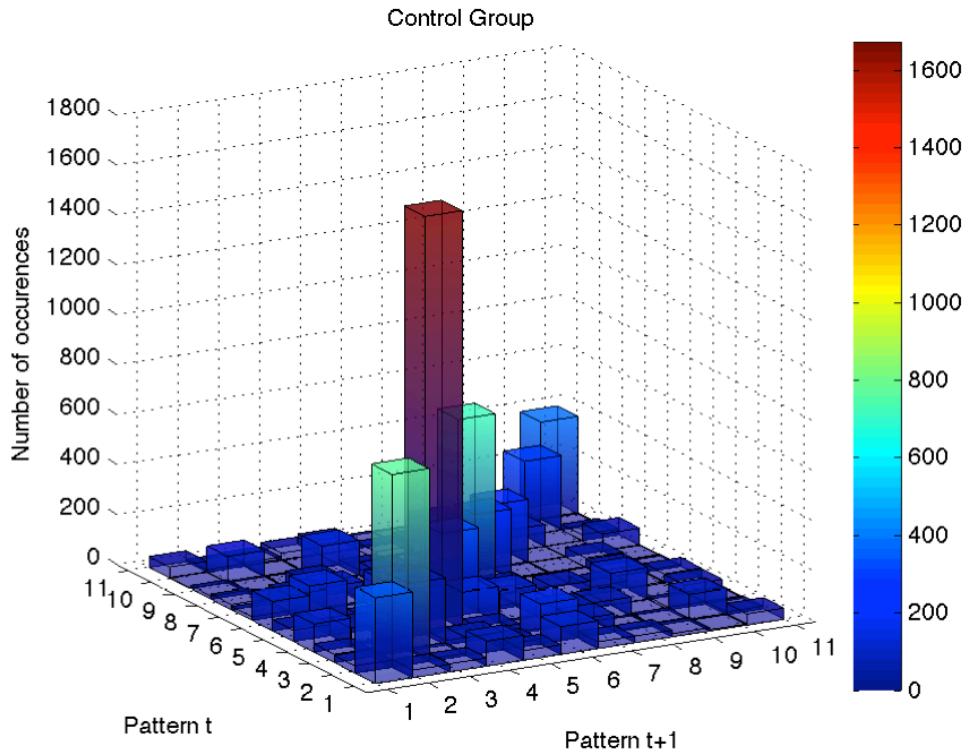


Figure 54. Representation of the exploitation (the diagonal, where a pattern is repeated) and exploration (left and right of the diagonal) exhibited by the control group.

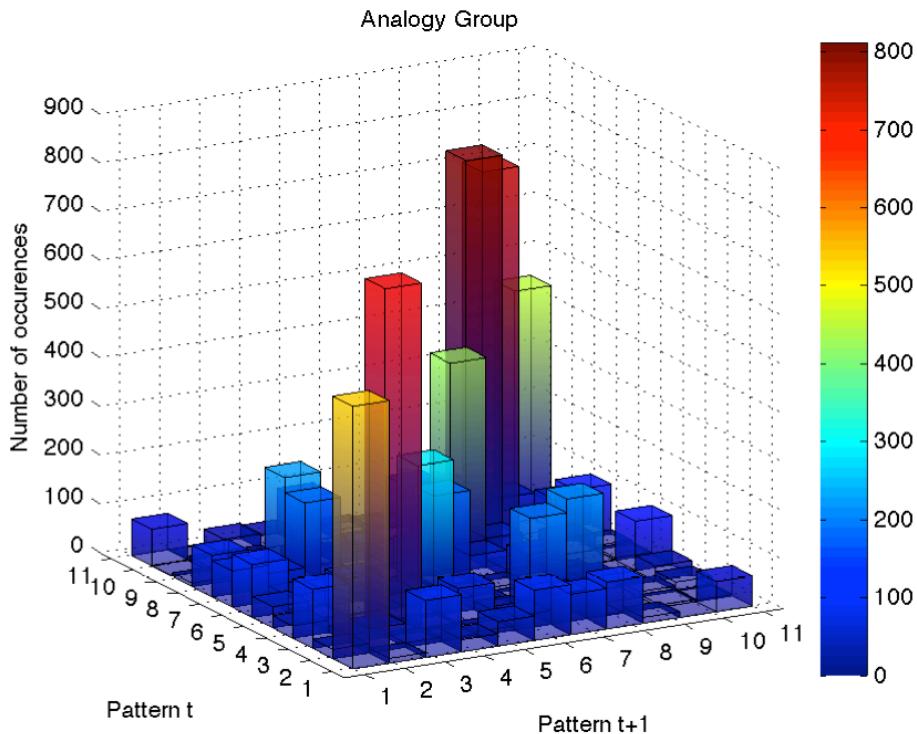


Figure 55. Representation of the exploitation (the diagonal, where a pattern is repeated) and exploration (left and right of the diagonal) exhibited by the analogy group.

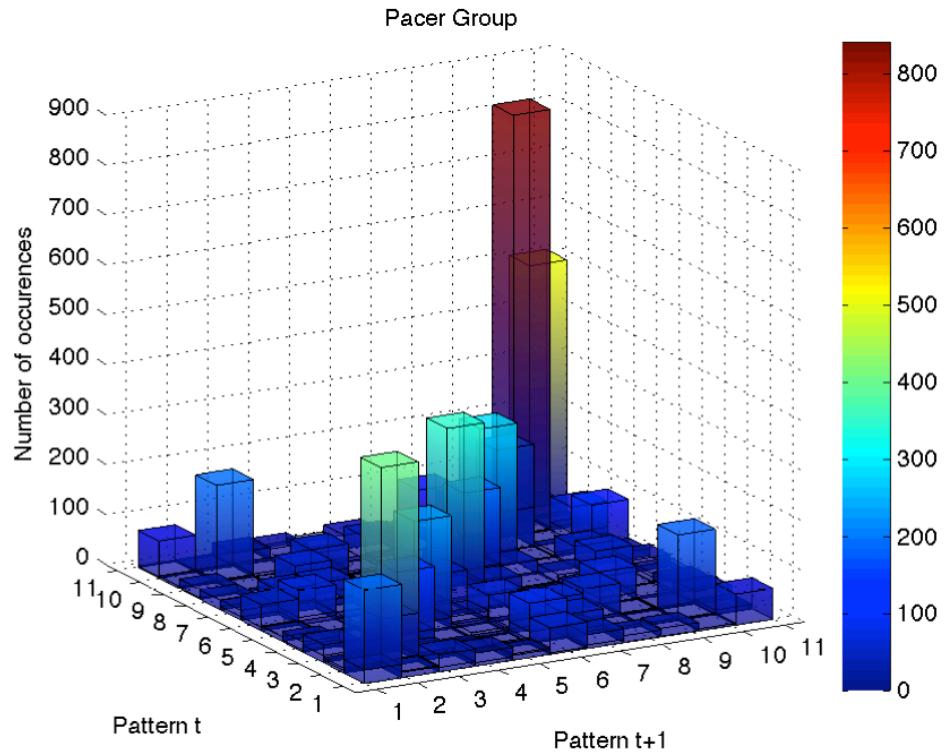


Figure 56. Representation of the exploitation (the diagonal, where a pattern is repeated) and exploration (left and right of the diagonal) exhibited by the pacer group.

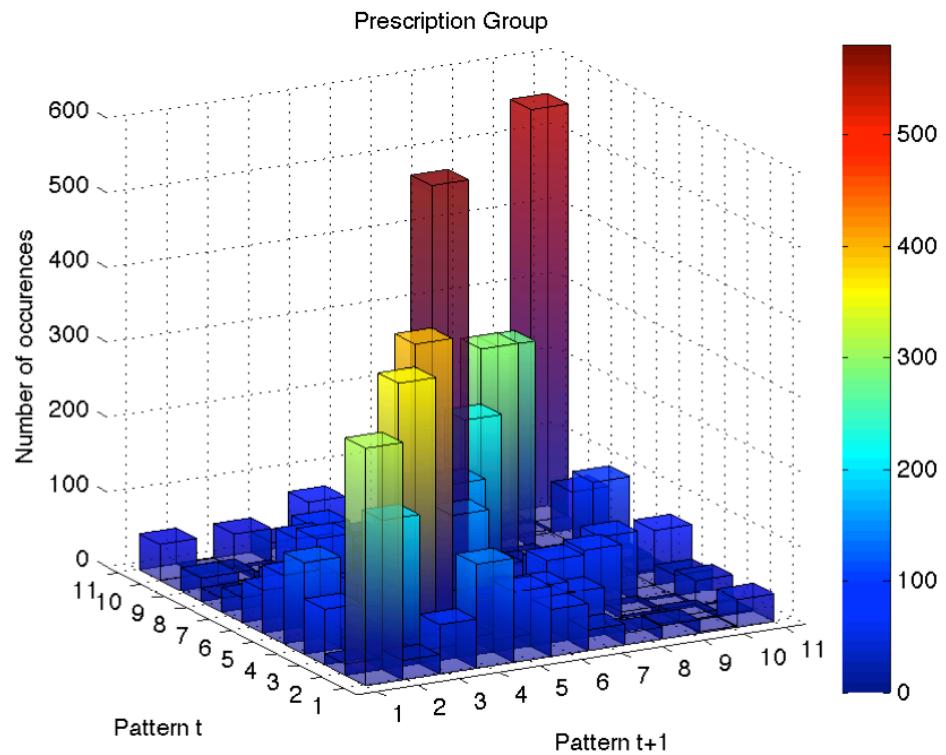


Figure 57. Representation of the exploitation (the diagonal, where a pattern is repeated) and exploration (left and right of the diagonal) exhibited by the prescription group.

Variability of the behavior

Cycle per cycle variability of the coordination. During the constrained trials, a three-way ANOVA (session x group x speed condition) performed on the Cauchy index showed a significant effect of the sessions ($F(12.93,26839) = 58.77, p < .001$, $\eta_p^2 = .028$, $\epsilon = .862$), as well as a significant effect of speed condition ($F(1,2076) = 1324.09, p < .001$, $\eta_p^2 = .389$) and a significant effect of the groups ($F(3,2076) = 95.39, p < .001$, $\eta_p^2 = .121$). In addition, three double interactions were significant ($p_s < .001$), as well as the triple interaction ($F(41.83,28951) = 15.80, p < .001$, $\eta_p^2 = .022$, $\epsilon = .930$).

Low swimming speed condition (Figure 58). The prescription group showed a Cauchy index higher than the other groups during the first session, showing that the prescription allowed to destabilize quickly the initial behavior. This prescription group was the only one showing a decrease of the Cauchy index during the learning process (after a maximal peak during session 3), namely that this group linearly decreased his variability during learning. This group showed only 2 sessions significantly different from the previous one (i.e. significance appeared only through a larger number of sessions, every 3-4 sessions), highlighting a relatively slight and linear decrease session after session (with session 16 significantly lower than session 1). This linear decrease of the Cauchy index is related to a good convergence, showing several successive steps in the decrease (e.g., Figure 59 and appendices).

Cauchy variable at low swimming speed

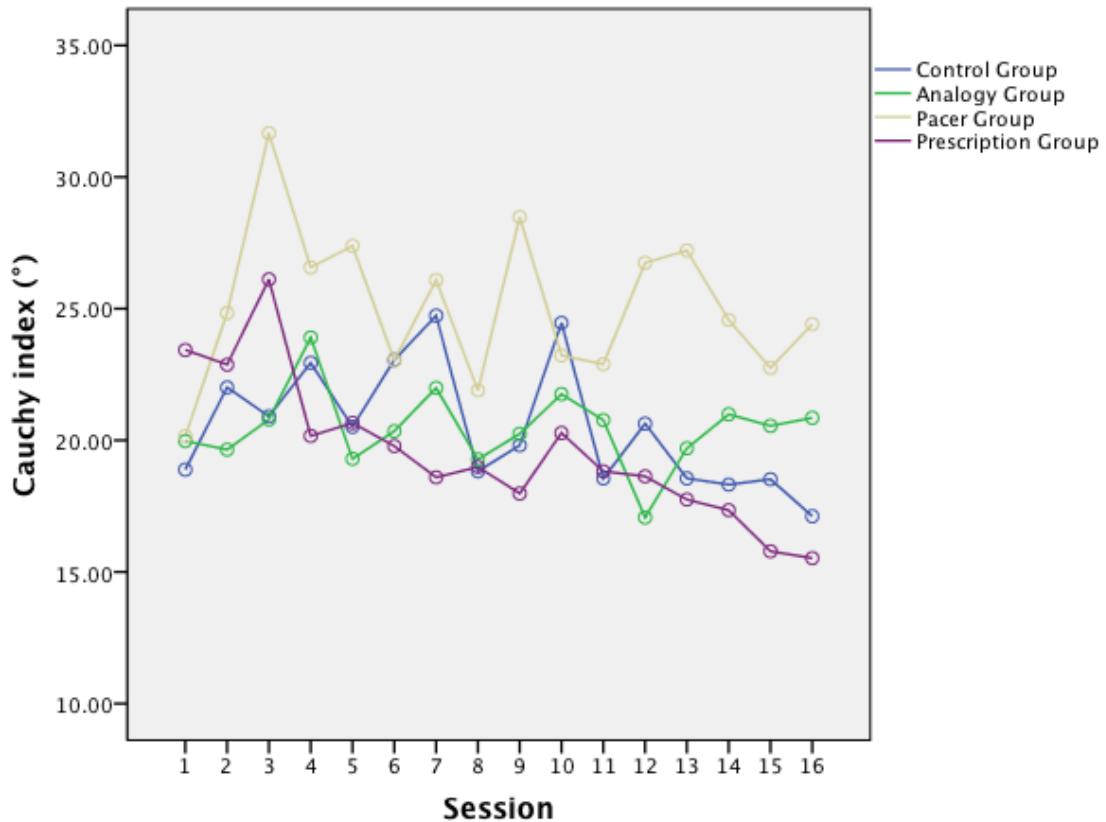


Figure 58. Cauchy index in low swimming speed condition in function of group and session.

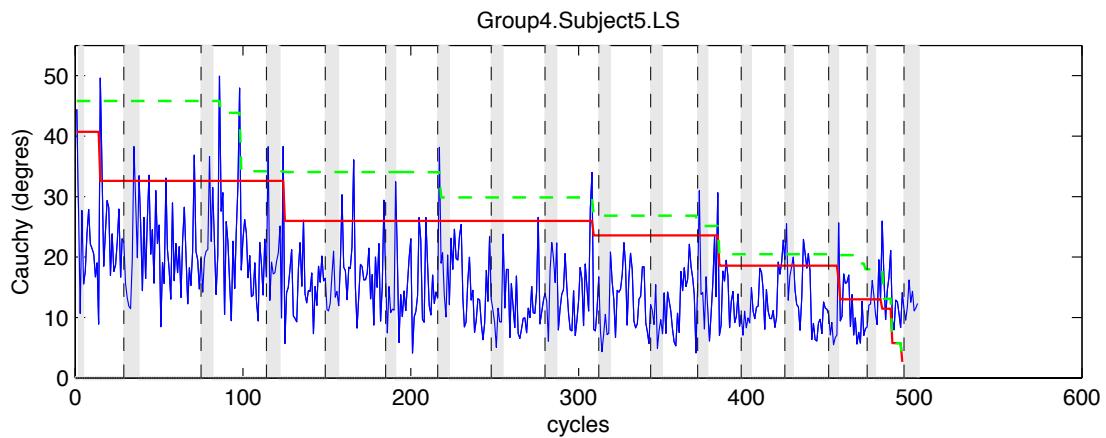


Figure 59. Cauchy index for participant 5 of the prescription group, showing the progressive decrease in variability and the good convergence of the variability (i.e. a diminution by regular steps of the amount of variability) (the continuous line represents the remaining amplitude of variability between two successive cycles, whereas the dotted line represents the maximal remaining amplitude of variability, Chen et al., 2005).

Conversely, the control group showed no significant difference between session 1 and session 16, but exhibited some fluctuations of the Cauchy index during the learning process (sessions 7 and 10 each higher than the previous one). However, these fluctuations were only unidirectional (i.e. essentially leading to more variability), namely that no session showed lower variability than sessions 1 and 16. These important fluctuations of the Cauchy index resulted in a large number of significant differences between adjacent sessions higher than the other groups (i.e. 6 sessions were significantly different from the previous one for this pacer group).

The analogy group presented the same characteristics than the control group, exhibiting increases and decreases of the Cauchy index during the practice, but no difference appeared between sessions 1 and session 16. This analogy group showed different peaks of variability during sessions 4, 7, 10 (sessions 4, 7 and 10 higher than sessions 1 and 16) and during session 12, but this session 12 showed lower variability than the other sessions.

Identically, the pacer group showed these fluctuations of the Cauchy index during learning (sessions 3, 7, 9, 12-13 significantly higher than their adjacent sessions). However after the first session, this group showed higher values of Cauchy index than the other groups (except during session 7, 10 where no difference appeared with the control group). This group also exhibited more variability during session 16 comparatively to session 1, suggesting that swimmers from this group were still deeply involved in an exploratory activity at the end of the learning process. In fact after the first session, this pacer group did not show any Cauchy index not higher than during the first session (i.e. as opposed to the prescription group) (Figure 58). Again, these important fluctuations of the Cauchy index resulted in a large number of significant differences between adjacent sessions higher than the other groups (i.e. 10 sessions were significantly different from the previous one for this pacer group).

Fluctuations of cycle per cycle variability exhibited by control, analogy and pacer groups reflected a relatively poor convergence, namely a high value of the Cauchy index even late during the learning process (e.g., Figure 60). Last, no difference appeared between sessions 13, 14, 15 and 16 for the control, analogy and prescription groups, showing a certain stabilisation of the Cauchy index at the end of the learning process for these groups, in contrast to the pacer group.

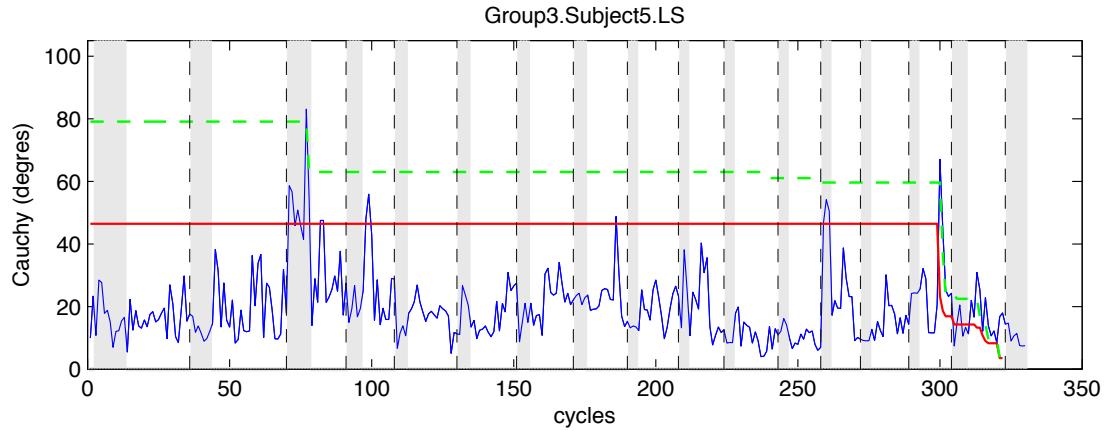


Figure 60. Cauchy index for participant 5 of the pacer group, showing the absence of decrease in variability and the poor convergence of the variability (i.e. a single plateau of the convergence) (the continuous line represents the remaining amplitude of variability between two successive cycles, whereas the dotted line represents the maximal remaining amplitude of variability, Chen et al., 2005).

High swimming speed condition (Figure 61). Identical phenomena to those observed in low speed condition were observed in high speed condition, but interestingly, the fluctuations observed for control, analogy and pacer groups in high speed condition did not occur during the same sessions as in low speed condition. In addition, this high speed condition seemed limiting the variability of the pacer group, namely that this group did not show any difference regarding the other groups in this speed condition unlike in the low speed speed condition. This pacer group is he only one that showed less variability in high speed condition regarding the low speed condition during all the sessions, while the other groups showed during some sessions a same amount of variability btween both speed conditions (1 session for the prescription group, 8 sessions for he analogy group and 7 sessions for the control group). Identically to the low swimming speed condition, prescription and analogy groups showed less differences between the session t and the previous session $t-1$ comparatively to control and pacer group (i.e. the significant differences appeared on larger intervals, approximatively every 3 or 4 sessions for the analogy and prescription group, while significant differences appeared mostly between every session for the pacer and control group [due to fluctuations]).

Identically to low swimming speed condition, the control group did not show a difference of cycle per cycle variability between session 1 and session 16, whereas the pacer group showed an increase in this cycle per cycle variability between session 1 and session 16. However, this pacer group showed during session 16 a Cauchy index equal to the one during sessions 5 and 13, suggesting that the increase between

sessions 1 and 16 might be due to high fluctuations rather than to a real increase with practice. However, the analogy group showed a similar pathway of the Cauchy index in this high speed condition, namely that these two groups exhibited a high Cauchy index during session 1, and a progressive decrease thereafter in order to reach a lower value during session 16 comparatively to session 1.

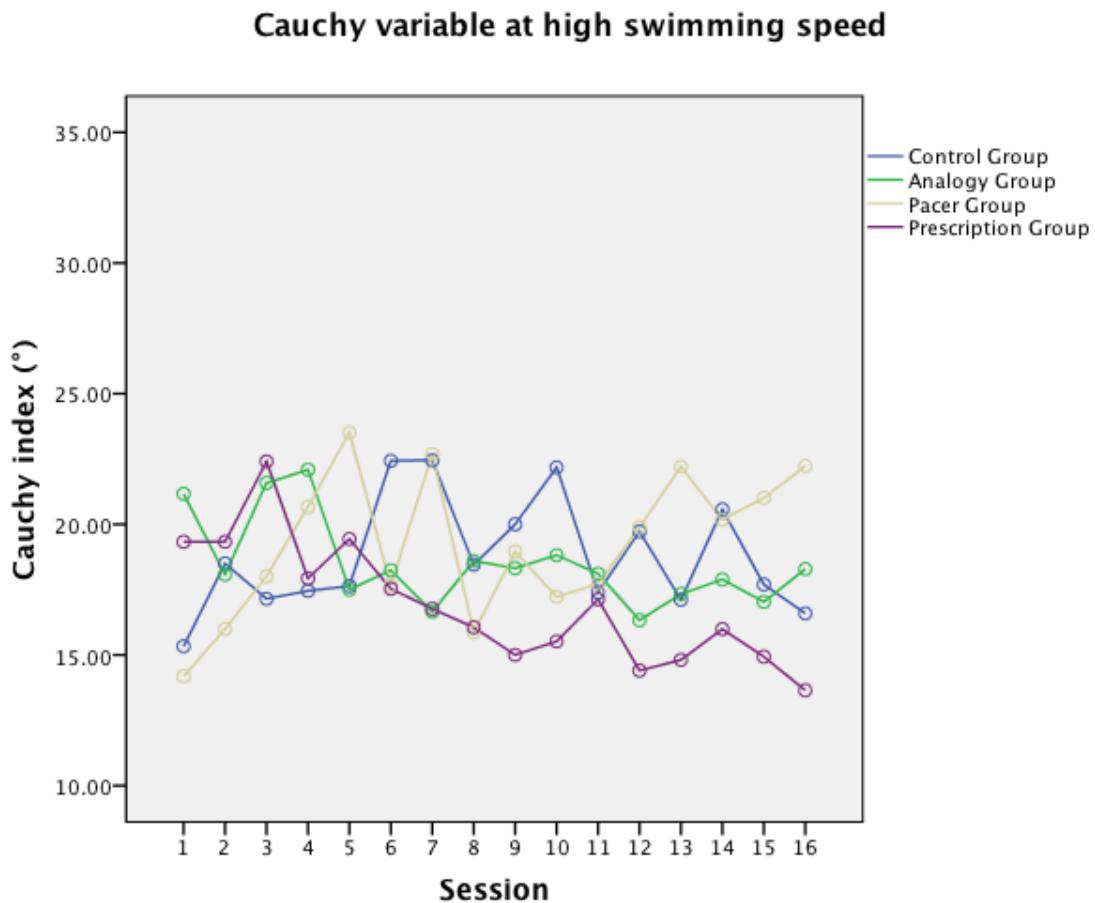


Figure 61. Cauchy index in high swimming speed condition in function of group and session.

Focusing mainly on the constrained vs. free practice effect, a four-way ANOVA performed on the Cauchy index highlighted a main significant effect of practice condition ($F(1,22) = 56.46, p < .001, \eta^2_P = .720$) as well as an interaction practice condition x group ($F(3,22) = 8.45, p < .001, \eta^2_P = .235$). Thus, post-hoc showed that independently of the group, swimming speed or session, learners exhibited a lower Cauchy index during free trials ($M = 18.47 \pm 0.75$) than during constrained trials ($M = 19.88 \pm 0.74$), excepted the control group that showed no significant difference (i.e. no difference between trials 1-2 and trials 3-10).

Cycle per cycle variability of independant oscillators. During the constrained trials, a four-way ANOVA (oscillators [elbow, knee] \times group \times speed \times session) showed a main significant effect of the oscillator on the cycle per cycle variability ($F(1,2076) = 13.37, p < .001, \eta^2_p = .866$). In addition, a quadruple interaction oscillator \times speed \times group \times session appeared significant ($F(42.69,29547.83) = 11.57, p < .001, \eta^2_p = .016, \varepsilon = .949$). Bonferroni post-hoc tests thereafter revealed that knees exhibited less variability than elbows (all $p_s < .019$), this was true independently of the speed and the group. In addition in low swimming speed, the pacer group showed a significantly higher variability of both elbows and knees comparing to the three other groups. More precisely concerning the knee variability, the prescription group showed less variability comparatively to the pacer and control groups ($p_s < .001$), except during the first session. Finally, for all the groups, the variability of the elbow oscillator was higher in low swimming speed condition rather than in high swimming speed condition ($p_s < .001$).

Discussion

The aim of this study was triple, namely: 1) studying qualitative and quantitative changes in the temporal dynamics of the behaviour during the learning process, 2) defining the effect of the use of different temporary additional constraints on the temporal dynamics of learning, 3) investigating the nature of the exploration and the different constraints on the temporal dynamics of the performance. Learners were asked to seek for an increase in stroke length, while maintaining a same stable speed during all the learning process. Results showed that all participants were able to respect the swimming speed conditions (i.e. 70 and 90% of their maximal speed $\pm 5\%$). However, groups receiving a temporary constraint in addition to the general goal of the task showed more canceled trials (i.e. more trials that did not respect the targetted speed). This information indirectly informs about the attentional cost of the task, or rather the double or even triple task that was requested (i.e. maintaining the speed + increasing the amplitude + answering the informational constraint about movement form). Thus, the pacer group was the one facing the most expensive task in terms of attention, whereas analogy and prescription perceived the task in the same manner slightly more expensive than the control group. This result was expected, that

is why we explicitly told to the experimental groups give the priority to the respect of the swimming speed and only secondly to the constraint (in that sense, no feedback was given to the learners about the respect of the additional constraint, e.g., a count of the two seconds for the analogy group or a count of the frequency for the pacer group). A specificity of the “pacer constraint” was also highlighted by the differences in terms of stroke frequency between free trials (i.e. trials 1 and 2) and constrained trials (i.e. trials 3-10). Indeed, when the analogy and prescription groups showed a difference between free and constrained trials only during the first session (i.e. they showed an instantaneous adaptation to the constraint that lead to rapid increase in performance), the pacer group showed a delay in the adaptation to the constraint, namely they took more time to exhibit the same performance during both free and constrained trials (i.e. they took more time to reduce the distance between their intrinsic dynamics and the behaviour emerging from the constrained trials). Last, the control group showed no significant difference between free trials and constrained trials, validating that there was no order effect between the trials. Concerning the general goal of the learning, the four groups increased their stroke length with learning, and exhibited an identical stroke length at the beginning as well as at the end of the learning process. Interestingly, when all learners showed no difference in stroke length between the two swimming speed condition during the pre-test, they exhibited a higher stroke length in low swimming speed condition than in high swimming speed during post- and re-test.

Globally, 11 different patterns of coordination emerged from all the trials performed by all learners from all groups and in all speed conditions. However, it appeared difficult to define one expert pattern within the 11 emerging patterns, mainly because of the use of the entire time serie of CRP in the cluster analysis. Indeed, some patterns exhibited for instance a beginning of the cycle close to anti-phase (i.e. close to the expert model), but thereafter a glide phase with a phase shift highlighting a glide position not highly effective. However, some patterns exhibited a value of CRP at the beginning of the cycle close to anti-phase, a value of CRP during the plateau close to 0° and a value of CRP at the end of the cycle close to anti-phase (e.g., patterns 7, 8 and 11). Therefore, these patterns were closer than the others to the expert pattern. Identically, some patterns exhibited a higher duration of the plateau and seemed more adapted to slow swimming speed conditions, at least to behaviours favouring the glide and therefore the search for high stroke length. Conversely, patterns that exhibited few intra-cyclic variability (e.g., pattern 4) were more close to

a novice pattern (Seifert, Leblanc, et al., 2010) and patterns showing no plateau of the CRP would be more suitable for high speed condition, due to the lack of glide (e.g., pattern 10) (Leblanc et al., 2007). In addition, a majority of participants did not exhibit a stable pattern at the end of the learning process, suggesting that they were still navigating between coordination and control stage of learning, therefore exploring the perceptual-motor workspace and seeking for a functional pattern. This result highlights the complexity of the to-be-learned pattern, relatively to the short learning duration proposed to learners. In a previous study in gymnastics, Delignières et al. (1998) already showed a similar phenomenon, namely that learners did not change their behavior after 10 learning sessions. Authors explained this results by the highly constraining nature of the task, limiting the possibility for learners to leave their intrinsic dynamics. However, the temporal dynamics of the behavior and the performance during the 16 sessions informs us about: i) the nature of the exploration occurring under the effect of practice, ii) the effect of additional temporary constraints on this exploration, iii) the relationship between the dynamics of the performance in function of the nature of the exploration.

Behavioral qualitative changes and nature of exploration

Focusing on the control group, results showed that most of the learners qualitatively changed their behavior when they were asked to increase their stroke length. More precisely, results showed that except participant 7 who did not change his behavior between pre- and post-test, all the participants exhibited at the end of the process a different pattern than at the beginning. Although the first session does not reflect a real beginner practice (i.e. a first entry into the water), participants showed high instability of their initial behavior during their first trials, highlighting that these learners were still seeking for a stable functional pattern, therefore navigating between coordination and control stage of learning (K. M. Newell, 1985). Obviously, participants did not exhibit the same and unique pattern of coordination at the beginning of the learning process, as suggested by previous results (e.g. Delignières et al., 1998; Kelso & Zanone, 2002; Nourrit, Delignières, Caillou, Deschamps, & Lauriot, 2003; Temprado, Della-Grasta, Farrell, & Laurent, 1997). However, it seems that the concept of similarity of novices' coordination patterns is still validated. In fact, novices preferentially adopted the same range of patterns (i.e. patterns 2, 4 and 6). Nevertheless in high speed condition, the number of novice patterns was restricted,

validating the hypothesis by Teulier (2004), suggesting that the existence of one unique novice pattern of coordination is not a general rule of learning, but is deeply dependant of task constraints. It therefore does not exist one novice pattern, but rather novice patterns (e.g. Seifert et al., 2011 in swimming), even novice trends, and whose expression strongly depends on task constraints (i.e. possibilities offered by the task). All situations where novices converged towards an identical pattern of coordination (e.g., Delignières et al., 1998 in gymnastics) would be specific cases where task constraints strongly limit the possibilities.

Interestingly, participant seven was the only one showing a stable pattern at the beginning of the learning. More precisely, the pattern exhibited by this participant defined an in-phase coordination, which is a feature of a novice coordination (Seifert, Leblanc, et al., 2010) and is known in bi-manual coordination to be highly stable (Kelso, 1995). In addition, this participant seven showed during practice very few variability (e.g. few switching ratio higher than zero, only four different patterns visited during the entire process and only two patterns stabilized at least during one trial), which was highlighted by a exploration/exploitation ratio less than the other participants of this control group (i.e. 0.231). Chow et al. (2008) noticed a same result during their experiment on soccer kick learning, namely that one participant did not change his behavior during the 12 sessions. Authors then suggested that the lack of variability during the learning process might reflect a lack of exploration, therefore leading to the absence of qualitative changes between pre- and post-test. The study of participant eight may validate this hypothesis. Indeed, participants seven and eight exhibited this pattern 4 during the pre-test, as well as an important exploitation of this pattern during learning (i.e. they exhibited many transitions from pattern 4 to pattern 4) (Figures 65 et 66). However, participant eight shows an exploration/exploitation ratio higher than participant seven, namely he explored more during practice, and this higher exploration might explain his change in coordination with learning. In addition, participant seven who did not explore during the practice was the only one who exhibited during the post-test the same patterns in both high and low swimming speed condition. This result thus highlights the functional role of movement variability during learning, that reflects the active exploration of the perceptual-motor workspace and allows the flexibility of the coordination needed to face different task/environmental constraints (Chow, Davids, Button, & Koh, 2008; Chow, Davids, Button, & Rein, 2008; Davids et al., 2004; Vereijken et al., 1992).

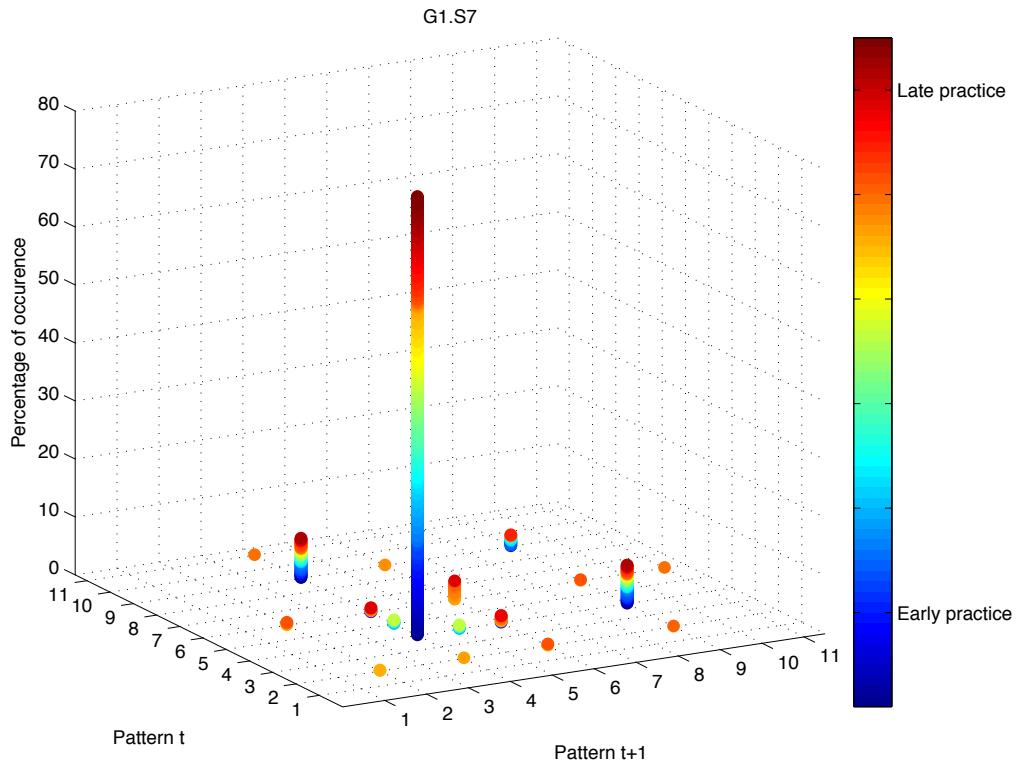


Figure 62. Presentation of exploitation (the diagonal where one pattern is followed by itself) and the exploration (on the right and left of the diagonal, where one pattern is followed by another), for participant 7 of the control group (color scale informs about the time of occurrence during the practice).

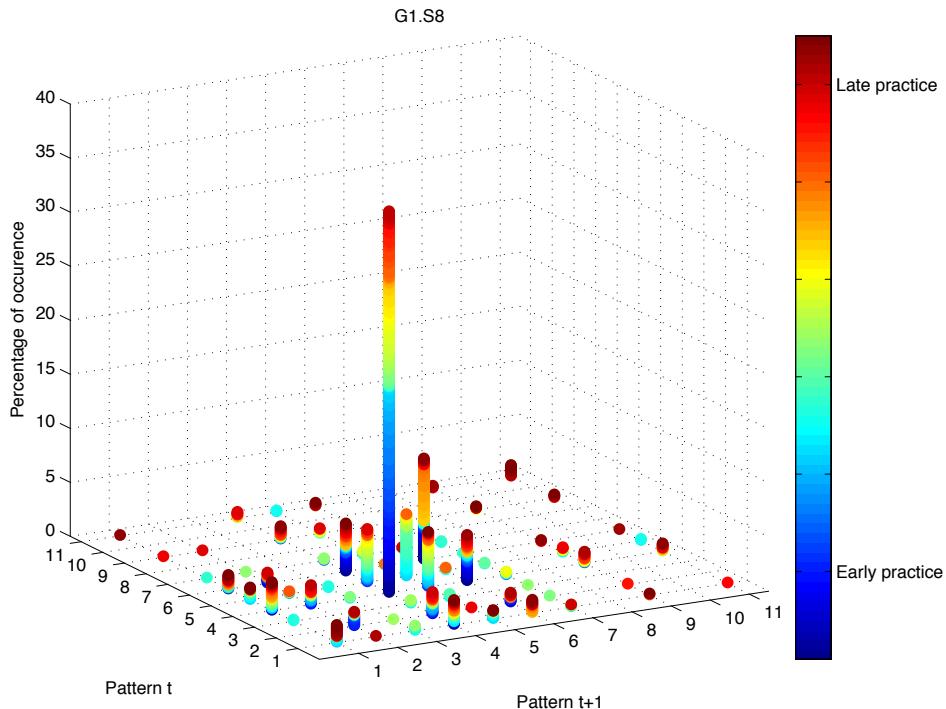


Figure 63. Presentation of exploitation (the diagonal where one pattern is followed by itself) and the exploration (on the right and left of the diagonal, where one pattern is followed by another), for participant 8 of the control group (color scale informs about the time of occurrence during the practice).

Nature of exploratory behaviors. During the sessions, all learners exhibited more patterns of coordination than they exhibited during the test sessions. Except participant seven, all participants therefore visited at least 9 different patterns, and some of which were (approximatively a third) stabilized then destabilized, validating the existence of qualitative reorganizations occurring during learning (Liu et al., 2006). This phenomenon has already been highlighted by Chow et al. (2008) who showed that learners were able during the learning process to temporarily stabilize different patterns. In addition, our results showed that learners were able to stabilize again their initial behavior late during the learning process, even if they stabilized other patterns before (e.g. Figure 64).

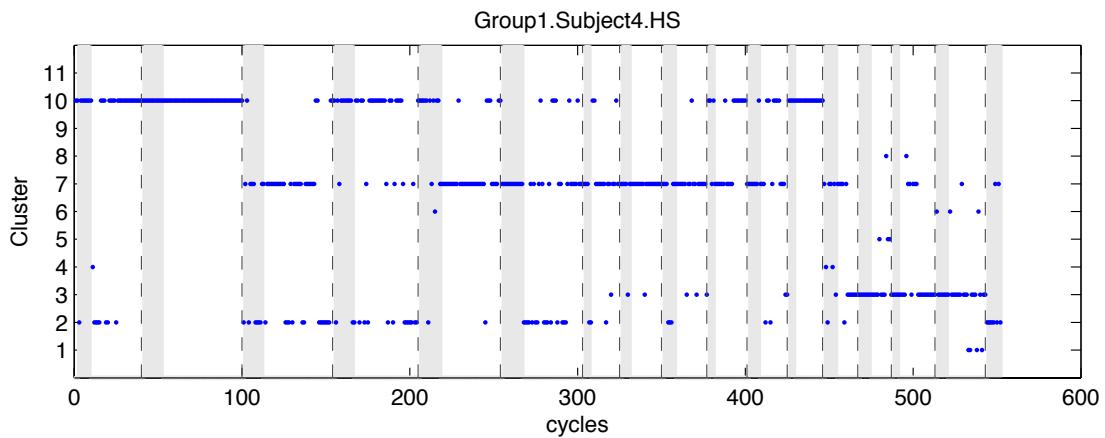


Figure 64. Patterns of coordination exhibited by the participant 4 of the control group, showing successive stabilizations of different patterns of coordination, including feed-back to the initial pattern (10) (in dashed line, separations between the sessions).

In fact, when Teulier and Nourrit (2008) defined a “cooperation between the initial coordination and the to-be-learned coordination” during the learning process (p. 45), it rather seems that there could be a *cooperation between stability and instability*. In other words, from a stable pattern (identical or not to the initial behaviour) that would behave like an anchor point, a certain instability would be possible and would reflect the exploration of the perceptual-motor workspace. Based on the switching ratio and the percentage of occurrence of the different patterns of coordination, this cooperation between stability and instability is reflected through a metastable regime (Kelso, 2012). The hypothesis of the presence of metastability rather than multi-stability is validated by cycle per cycle changes of coordination (e.g. Figure 65), as observed by Nourrit et al. (2003) on ski-simulator. Indeed, the presence of multi-

stability would require a perturbation of the initial behavior by an intentional information (Schöner & Kelso, 1988b). However, a paramount difference between cycliv and discrete activities is the role potentially played by intention on the behavior (Rein, Davids, et al., 2010), and it seems difficult to envisage in a cyclic activity that the learner is able to intentionally modify cycle per cycle his coordination. In addition, the absence of a switching ratio equal to 1 shows that the cycle per cycle changes of coordination appeared punctuated by period of relative stability of the coordination, validating the presence of metastability (i.e. the presence of both dynamical stability and dynamical instability) during the learning process.

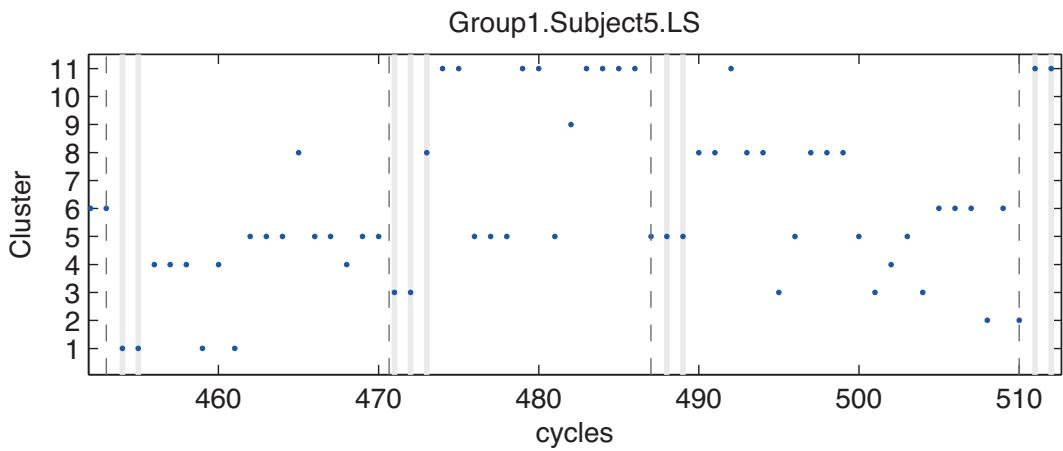


Figure 65. Sessions 13, 14 and 15 for the participant 5 from the control group, showing cycle per cycle changes in coordination (each point represented a cycle, dotted lines separate the sessions, in grey the free trials).

In terms of exploratory strategy, previous results tend to highlight the use of hybrid strategies, including periods of variability around a relative stable pattern. In fact, if we consider the distance of exploration (i.e. the cycle per cycle variability of the relative phase, in degrees), we note in this control group that there is no difference between the beginning and the end of the learning (i.e. resulting in a poor convergence). However, learners showed fluctuations of the cycle per cycle variability, but these fluctuations were only temporary increases, namely that minimal values were observed during the first and last sessions. These fluctuations of the variability have already been observed by Vereijken et al. (1992) during learning on ski simulator, and were considered as a necessary ingredient to learning. These fluctuations in variability argue in the sense of a hybrid search strategy, as they reflect some periods of relative low exploration (i.e. search around the anchor point)

interrupted by moments of high exploration (i.e. search of a new anchor point). Again, the nature more or less constraining of the task appeared strongly impacting the ability to explore. More precisely in high swimming speed condition, the Cauchy index of the relative phase, but also of the independent oscillators, was lower than in the low swimming speed condition, highlighting the impact of forward resistances on the ability to explore.

Our results also validate the hypothesis of Teulier and Nourrit (2008) on the longer period of exploration needed when learners are facing highly constraining task, in contrast to less constraining task. Indeed, an interaction between test-session and swimming speed condition was observed, namely that more different patterns were observed during the first session in low swimming speed (6 different patterns and 1 stabilized) than in high swimming speed (3 different patterns and 3 stabilized). Conversely during post-test, four participants in low swimming speed had stabilized a new pattern when six different patterns were present, whereas only one participant had stabilized a pattern and nine different patterns were still exhibited in high swimming speed condition. These results highlight the idea that a slightly constraining environment can lead learners to modify rapidly their behaviour, whereas a highly constraining environment requires more time to stabilize a new behaviour, probably because it allows less exploration (i.e. it limits the expression of degeneracy). The relative stability of the Cauchy index during the late sessions in low speed condition argues in that sense, whereas this stability did not appear in high speed condition.

Effect of additional temporary constraints on the qualitative changes occurring during learning.

Effect of additional constraint on the nature of the exploration. Broadly speaking, the different constraints used in this experiment showed an effect on the predominance of certain patterns of coordination. More precisely while the control group showed predominantly the patterns 2, 4 and 6, the use of an analogy limits the appearances of these patterns 2, 4 and 6 to favour patterns 1, 3, 7, 8 and 9. The pacer group showed more cycles associated to the pattern 10, and less associated to patterns 1, 2, 3, 4, 5 and 6 while the prescription group exhibited mostly the patterns 5 and 9 and less patterns 2, 4 and 6. Interestingly, patterns 2, 4 and 6 were principally exhibited during the beginning of the learning process, and the fact that the

informational constraints limited their occurrence may reveal the ability of these additional constraints to favour exploration (i.e. to leave the initial behaviour). As Newell (1986; 1989) suggested, the acquisition of a new coordination is the result of a process aiming to manage interacting constraints acting on learners during practice; modifying constraints can lead to different emerging coordinations. Whatever the nature of the additional constraint, learners showed during they free trials (i.e. trials 1 and 2) a switching ratio lower than during the constrained trials (i.e. trials 3-10), which showed that these constraints were able within a session to put learners into an explorative activity through the need for adaptation to the constraints (Davids et al., 2008). This idea is corroborated by the higher Cauchy index (i.e. higher variability) exhibited during constrained trials compared to free trials. In addition, adding a temporary constraint during the practice did not modify the number of visited patterns during the entire process, but limited the number of stabilized patterns. This was the case mainly in low swimming speed condition, suggesting a strong impact of task constraint on the explorative activity exhibited by learners.

Prescription as a temporary constraint. Paradoxically, this constraint that was supposed to prescribe a movement and limit the exploration has generated a higher cycle per cycle variability of the coordination than the three other groups, since the beginning of the learning process (during sessions 1, 2 and 3). Thereafter in both swimming speed conditions, this cycle per cycle variability decreased in a relative linear manner (i.e. each session showing less variability than the previous one), in order to reach a minimum during the post-test. This progressive decrease resulted in a good convergence, namely showing regular steps in the curves defining the remaining variability (Figure 59). This convergence defines a progressive rapprochement of the learner's coordination towards a targetted coordination (Chen et al., 2005). Associated to this decrease in the distance of exploration, this prescription group showed a exploration/exploitation ratio higher then the other groups, and especially a ratio higher than 1 signifying that this constraint led learners to more exploration than exploitation. The exploratory strategy exhibited by learners from this group might refer to a local strategy, with an important exploration at the beginning and a continuous decrease therafter. In addition, it seems that this constraint limits the stabilization of explored patterns, namely that this group showed an average of two (in high speed condition) to three (in low speed condition) stabilized patterns, but did not inhibit the exploration as shown by the exploration/exploitation ratio of 1.10.

Pacer as a temporary constraint. Conversely to the prescription group, the pacer constraint was assumed to prescribe the least a to-be-learned pattern. This constraint generated qualitative reorganizations that differed from the control practice. This was in line with previous use of a metronome in movement learning (Ford et al., 2007). Results showed more precisely that this type of non-prescriptive constraint had an opposite impact on the cycle per cycle variability of the coordination, compared to the use of a prescriptive constraint. Thus in low swimming speed condition, this pacer group showed a low variability at the beginning of the learning process, and a higher value at the end, suggesting that this group was still involved in an exploratory activity during the post-test. In general, a higher variability of the CRP was observed for this groups compared to the three other groups, with an important variability between the sessions (i.e. identically to the control group, but with higher peaks of variability). The non-prescriptive nature of the constraint allowed as expected a larger exploration of the perceptual-motor workspace, resulting in a large amount of sessions showing a mean of Cauchy index higher than 25° (which was never the case for the other groups). Identically to the control group, the fluctuations of the Cauchy index during the learning process were associated to a relative poor convergence (i.e. a high amount of variability late during practice), suggesting that this group also preferably used an hybrid search strategy (Figure 60). This hypothesis is validated by the relative low exploration/exploitation ratio of this group, that did not appear significantly higher than the control group and that attest a tendency to repeat a pattern of coordination during learning. Last, this pacer group was the only one to show a speed effect on the cycle per cycle variability of the coordination and elbow oscillator, namely that the higher variability exhibited by this group in low speed condition was not present in high speed condition, validating again the impact of the task and environmental constraints on the learner's exploratory ability.

Analogy as a temporary constraint. The analogy group appeared as an intermediate group positioned between the pacer group and the prescription group. More precisely, this group also showed fluctuations of the Cauchy index during practice (associated with a poor convergence), but without showing values as high as the pacer and control group, suggesting that the information on the movement form of the arms channelled the exploration. Interestingly, this channeling of the exploration did not change the nature of the exploratory process. Indeed, like the control and pacer groups, this analogy group showed a lower exploration/exploitation ratio than the prescription group, as well as a poor convergence of the coordination, suggesting

the presence of a hybrid search strategy. Finally, it seems that this analogical constraint was also impacted by the speed condition, namely that in high speed condition this group did not show any fluctuations of the Cauchy index after session five. In fact in this high swimming speed condition, the exploratory behaviour of the analogy group was close to the one of the prescription group, showing a high variability at the beginning of the learning process, and a stabilization after session five accompanied to a lower value at the end of the process.

Constraints to guide the nature of the exploratory behaviour. In summary, additional temporary constraints led learners to adopt different patterns of coordination during the exploration, but also to modify the nature of the exploratory strategy. Thus, when a “target” pattern is provided to learners, they logically tend to get closer gradually to this pattern, but without inhibiting entirely any use of qualitatively different patterns during practice. In addition, a certain linearity appeared in the exploration/exploitation ratio regarding the prescriptive nature of the constraint, namely that the control group showed the higher propensity to exploit; the pacer group showed a slightly superior tendency to explore; the analogy group showed again a higher tendency to the exploration than the pacer group, whereas the prescription group exhibited the highest level of exploration. Even if the results of the pacer and analogy groups validate the hypothesis on the use of implicit instruction favouring exploration (Davids et al., 2008; Maxwell et al., 2000; Vereijken et al., 1992), results from the prescription group questioned the existence of an optimal ratio between exploration and exploitation during learning. Indeed, the presence of more exploration than exploitation might reflect the absence of a real exploration, but rather a high instability of the coordination (i.e. rather than metastability, Kelso, 2012), which may be due to a strong competition between the behavioral information and the learner’s intrinsic dynamics. In other words, does too much exploration not mean high instability? Conversely, does exploration not need at some time a certain stability or repetition of a coordination, so that the learner can actually explore higher order derivatives around this pattern?

Finally, the absence of instability of coordination at the end of the experiment is a strong limitation of the study, suggesting that the to-be-learned skill was too complex relatively to the duration of the available learning period. From this, it was difficult if not impossible to define a constraint as qualitatively more effective than another, mainly as the non-stabilized patterns of coordination defined the exploration,

therefore did not represent a feature of what will be stabilized at the end of the exploratory process. Also, exploring an inefficient pattern of coordination might not be inefficient, as it does not signify that the learner will not stabilize a biomechanically effective pattern thereafter.

Effect of exploratory behaviors and informational constraints on the dynamics of the performance

Broadly speaking, the different constraints exhibited during the practice led to different pathway between the groups in the performance dynamics, but without clearly express a relationship between the nature of the exploration and the performance dynamics (i.e. the prescription group did not clearly differ from the others). In low swimming speed condition, the analogy and prescription group showed an early decrease of the frequency (i.e. an early increase in stroke length), that which brought these groups to achieve their minimum frequency from session 8. Conversely, the control group showed come latency in the frequency decrease, and thereafter a gradual decrease until the last session of post-test. These results corroborated previous uses of analogy in motor learning shoing that an analogy could overcome the problem of performance increase encountered in implicit learning (i.e. a lower performance due to dual tasks), while promoting an implicit learning (Lam et al., 2009b; Masters, 1992; Maxwell et al., 2000). In addition, the early increase in performance observed in the analogy group is in line with the work of Liao and Masters (2001) in table tennis, whereas Lam et al. (2009) reported a latency in performance increase for the analogy group in basket-ball hook-shot learning. This difference might be explain by the different task involves, especially by the relationship existing between movement form and movement performance. Indeed in the present swimming task, the analogy focused on the glide, which is directly related to the increase in stroke length (or decrease in stroke rate), whereas in basket-ball (Lam et al., 2009), the analogy focused on the technique of shoot that may be less directly related to the performance (i.e. to score a basket). Concerning the pacer group that showed an important variability of the behaviour, the decrease in frequency showed different successive steps. In fact, after a first decrease between session1 and 2, further decreases occurred every three of four sessions. These results might validate previous conslusions from Liu et al. (2006; 2010) stipulating that qualitative

reorganizations in behaviour could lead to non-linear modifications in performance. For instance, Liu et al. (2010) showed in a roller-ball task that the curve of performance followed a S-shape curve, with a strong increase in performance associated with qualitative reorganization of the behaviour. In the present study, these abrupt changes in performance might be associated to higher exploration observed in this group (i.e. the use of highly different patterns). A large amount of exploration could lead to a late increase in performance. Arguing in that sense, the prescription and analogy groups that showed the lowest Cauchy index also showed the earliest improvement in performance.

However, results in the high swimming speed condition limit the scope of this hypothesis. In fact in this speed condition, the analogy and prescription groups decreased their frequency essentially between the first and the second session, and showed their minimal value of frequency already during session four. Conversely, the pacer group again showed a decrease of frequency by different steps. Interestingly, the prescription and analogy also showed an early stagnation of the Cauchy index (i.e. from session five) in this high speed condition, whereas they exhibited an identical phenomenon in low swimming speed condition but in a less pronounced manner. Thus, it seems that the increase in performance (i.e. the decrease in frequency in our case) might be associated to the learner's exploratory ability, and that the decrease in exploration leads to a stagnation of the performance. Such hypothesis has been already investigated in a study concerning learning to reach a target with a joystick, where a high early variability of the behaviour (i.e. during the first five sessions) was correlated to a better performance during the last five sessions (Stafford et al., 2012). In order to validate this hypothesis, we should now propose a longer time of practice, so that all learners could stabilize a final behaviour and an associated performance (i.e. reach or even overpass the control stage of learning).

GENERAL DISCUSSION

The objective of this work was to investigate the nature of exploratory behavior during motor learning. Our work differs from earlier research on this topic as we tried to temporarily constrain the learners' perceptual-motor workspace during practice sessions in order to guide and even optimize their exploratory behaviors. Within the dynamical systems framework, motor learning was assumed to be based on the stabilization of functional and adaptable movements that emerged from the set of constraints acting on the learners. From this perspective, learning situations must respect the dynamics of the task within its performance context (Davids et al., 2008; Davids, 2012; Pinder, Davids, et al., 2011).

Based on the original works of Egon Brunswik (1955), Pinder et al. (2011) referred to *representative learning design* to emphasize the importance of the performance context in the conception of learning designs. As suggested by Gibson (1979), different information sources present different affordances to practitioners as they carry out their actions, and it is thus essential to take these sources into account in the learning environment (Pinder, Davids, et al., 2011). The decontextualization of a learning task by decomposing it into a series of subtasks or laboratory tasks results in the loss of its environmental, cultural and social complexity and, in fact, learners end up losing the essence of their own motricity (Bril, 2002). This is similar to the observation that laboratory tasks often fail to capture the complexity of motor learning (Wolpert, Diedrichsen, & Flanagan, 2011). Even though our approach may have led to additional methodological constraints, this study deliberately took into account the environment of performance during learning tasks. In this regard, Pinder et al. (2011) were able to show in cricket that using an "automatic pitcher" evoked different motor responses than those evoked by a "real" pitcher. The removal of information sources usually provided by the environment was unsurprisingly shown to limit the ability of pitchers to use this relevant information to support their actions and thus create and refine the information-movement coupling (Pinder, Renshaw, Davids & Kerhervé, 2011). What then should we think of learning how to swim, not so long ago, out of the water (Figure 66)? Tasks that do not respect the representative learning design do not appear to allow for (i) reliable diagnosis of the critical aspects

of performance and behavior or (ii) the implementation of appropriate interventions to develop skill.



Figure 66. Use of a harness to learn the breaststroke in the early 20th century.

On the basis of ecological dynamics theory (Araújo et al., 2006), which supports both the tools and concepts of dynamic coordination and ecological psychology (sometimes referred to as the natural physical approach [e.g., Davids, Handford, & Williams, 1994]), we thus investigated over the course of this work the concept of functional variability (Newell et al., 2006) and the value of exploring the perceptual-motor workspace during learning tasks, even for activities that seemed to ultimately required the development of an expert coordination pattern.

The need to learn an expert coordination in breaststroke. Our first study highlighted the arm-leg coordination pattern exhibited by experts. Specifically, experts showed a pattern over the course of a cycle that switched from an antiphase relationship to in-phase and then again to antiphase by the end of the cycle. In contrast, novice swimmers did not reach antiphase mode at either the beginning or end of the cycle (i.e., they exhibited start and end values closer to a phase shift of -100°), and the expert coordination thus emerged as the most variable coordination

pattern in terms of intra-cycle variability (Seifert, Leblanc et al., 2011, 2010). However, the novice population of this experiment showed a more advanced coordination than the population of real beginners. Indeed, the real beginners showed only one of the fundamental coordination modes over the entire cycle; namely, in-phase (i.e., simultaneous flexion-extension of the two pairs of limbs) or antiphase (i.e., elbow flexion during knee extension or vice versa) (Seifert, Leblanc et al., 2010). In contrast, the experts' high intra-cyclic coordination variability limited the superposition of contradictory actions in terms of propulsion (i.e., arm propulsion and leg recovery or leg propulsion and arm recovery) for a maximization of propulsive action. Interestingly, the experts' maximization of propulsive actions reduced their efficiency index (i.e., an increase in the intra-cyclic variations of instantaneous velocity) (Leblanc et al., 2007). Expert behavior thus seemed to consist more in a search for effectiveness (i.e., maximize the propulsive action) rather efficiency, as expected by dynamic approaches (as suggested by Sparrow & Newell, 1998; Sparrow, 1983). One of the main reasons might be the underwater limb recoveries, which create strong resistance to progress, making it necessary to search for maximum propulsive effectiveness. In other words, being unable to prevent the strong resistance during the arm and leg recoveries, experts have no solution but to maximize their propulsive actions to increase speed. These results highlighted the specificity of expert breaststroke; namely, that expert coordination is quite specific and consists of a change from antiphase to in-phase and then back to antiphase, all within the same cycle (i.e., over a period of 1 to 2 s).

Because of this relative complexity of coordination, which is reflected by the absence of the stable relative phase value observed in bimanual (Zanone & Kelso, 2002; Zanone & Kelso, 1997) and postural (Faugloire et al, 2009) coordination, a *scanning task* with the aim of defining the intrinsic dynamics of beginners is relatively difficult in swimming. Although it is possible to request in-phase or antiphase coordination over an entire cycle, it is difficult to ask participants to achieve a coordination phase shift of 30°, 60° or 90° over the cycle. Moreover, such a phase shift does not include the pattern to be learned, which is in fact a succession of antiphase, in-phase and then again antiphase coordinations. In other words, experts show coordination changes even within a cycle. A *scanning task* would thus require asking participants to perform a phase shift at each key point; such as a 60° shift at the beginning of the cycle, followed by 90° during the glide, and a 60°shift to finish, and this for all possible combinations.

To conclude, expert coordination appeared to be biomechanically efficient, but the maintenance of the expert's efficient behavior (i.e., in the sense of reaching Newell's final learning stage, 1985) did not seem to be respected. Nevertheless, the experts showed flexibility in their coordination patterns when faced with various environmental conditions (Chow, Davids, Button, & Koh, 2008).

Degeneration as supporting the functional role of variability. This adaptation of coordination to constraints reflects one of the possible expressions of the degenerative nature of neurobiological systems (Edelman & Gally, 2001; Mason, 2010; Whitacre, 2010). More specifically, the degenerative architecture of the neuromusculoskeletal system was put forward in the second study by showing that it allows for the stability of coordination under external constraints, the flexibility to cope with environmental changes, and pluripotentiality so that coordination pattern changes are possible (Whitacre & Bender, 2010; Whitacre, Rohlfschagen, Bender, & Yao, 2012). In this regard, even if experts seem to use a clearly identifiable pattern, Study 2 was able to highlight the coexistence of several coordination patterns exhibited by swimmers navigating between stages of coordination and control and all performing the same task (i.e., functional equivalence). Moreover, these different patterns brought all learners to the same level of task proficiency (i.e., the same performance in terms of swimming speed and movement effects). This characteristic of degeneration suggests the possibility of exploring the workspace even though a specific coordination is to be learned. However, the different coordination patterns that emerged showed differences in angular amplitude or rotational speed of the elbows and knees, which are considered higher-order derivative variables (sometimes called superficial coordination parameters) (Chow, Davids, Button, & Koh, 2008). In fact, the observed differences in these variables suggest that the coordination patterns were exhibited by the participants so they could try different relationships among the high-order derivative variables, effects of movement and coordination. Interestingly, movement variability was greater at the elbows than the knees, indicating that the elbows offered more potential for change than the knees (whose oscillations appeared highly similar across emerging groups). These results confirm previous work on multi-segmental coordination showing that the arms were more implicated in regulating coordination (Kelso & Jeka, 1992). In addition, this potential for variation appeared severely limited by the constraints acting on the participants (i.e., degree of resistance to progress); that is, the more restrictive the environment was, the more

limited the expression of degeneration appeared to be, suggesting a constraint effect on the capacity to explore. An important aspect of the influence of constraints on the degenerative aspect of coordination was that the qualitative reorganization of the neuromusculoskeletal system, which operates under the influence of constraints, was not linear. Thus, the coordination pattern exhibited in an environment with few and/or weak constraints did not define the pattern exhibited when the environmental constraints increase proportionally. This result was defined as an expression of the multipotentiality offered by the degenerative architecture; that is, identical elements (i.e., mechanical degrees of freedom) that can be organized in a certain way in a specific condition were able to reorganize completely differently (and sometimes by involving additional degrees of freedom) in other practice conditions. It is therefore the degenerative nature of neurobiological systems that permit exploration during learning (i.e., specifically defined as "the reproduction of movements (slightly) different or by using a different neuromusculoskeletal organization" [Goldfield Kay, & Warren, 1993; van der Kamp & Savelsbergh, 1994]). The last study specifically emphasized that the exploratory behavior operating during motor learning was the privileged site for the manifestation of neurobiological degeneration, mainly through its multipotential character.

Metastability and exploration of the workspace. During learning periods, neurobiological degeneration results in periods of metastability (Kelso, 1995). Our last experiment in this direction highlighted this metastable regime which combines dynamic stability and dynamic instability (Kelso & Engström, 2006). These periods of metastability offered by the expression of degeneration support innovation (Hristovski et al., 2009). Indeed, as no pattern here actually appeared to be stable, the metastable regime allowed new organizations and new coordination patterns to emerge, given that at this moment the intrinsic dynamics were (temporarily) no longer an attractor. The perceptual-motor workspace (Figure 67.A) represented quite well these periods of metastability during which learners explored "rough" zones (Button, Chow, & Rein, 2008, p. 543), with slight fluctuations in the collective variable referring to zones of both low stability and low instability. Sometimes, however, the learners seemed to stabilize a coordination pattern, yet they showed many diverse stable patterns over the various sessions and sometimes returned to stability in an initial pattern in much later sessions. As suggested Teulier and Nourrit (2008), the return to an initial coordination might correspond to a kind of retreat to a stable refuge coordination. Nevertheless, the observation that learners stabilized patterns other than

their original pattern (without these patterns being exhibited post-test) suggests that these temporary stabilizations were not only a refuge during exploration, but that they defined a specific strategy of exploration; namely, non-local (or hybrid). In fact, this strategy is defined by a succession of stabilized patterns with some fluctuation/exploration around these temporarily stable patterns. This hypothesis was supported by the changes in the Cauchy index, which defines the amount of variability or exploration (in degrees of CRP) from cycle to cycle and which showed a certain stability across sessions. Indeed, a blind strategy would result in significant cycle to cycle fluctuations, with theoretically an in-phase pattern following antiphase coordination (Cauchy index close to 180°) or two successive in-phase patterns (Cauchy index close to 0°), and this in a totally random way. In contrast, a local strategy would lead to a more linear decrease in the amount of exploration as the coordination pattern to be stabilized is reached.

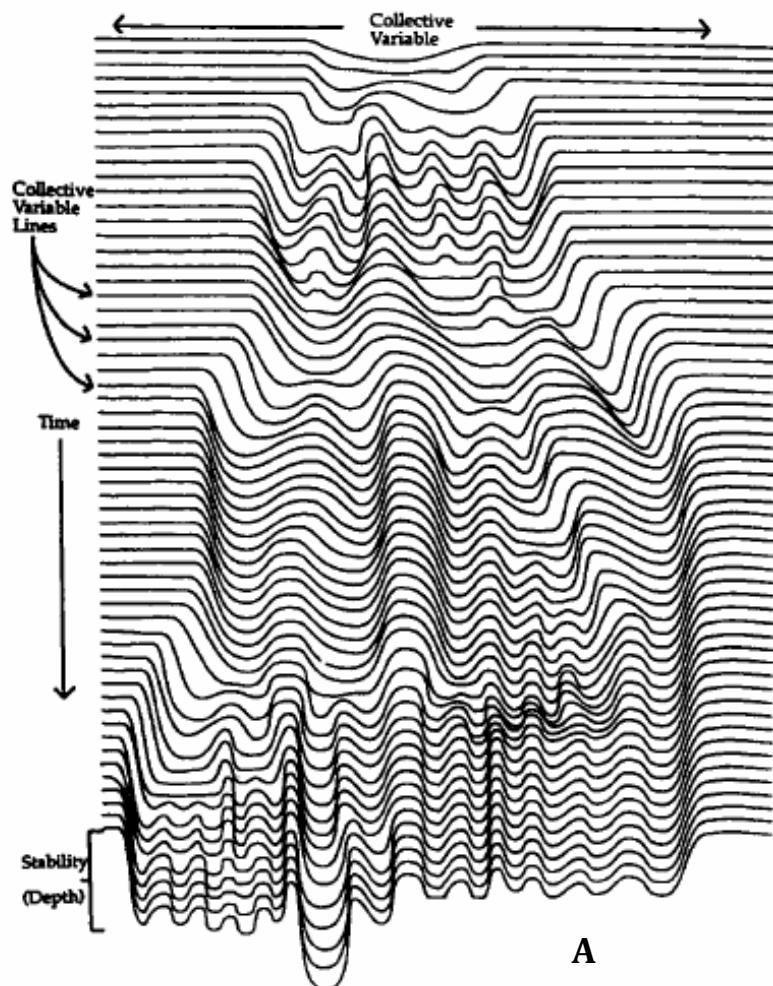


Figure 67. Representation of the workspace (Thelen, 1995) and its evolution over time (from the top toward the bottom).

In fact, our second experiment highlighted the observation that, through the exploration of this workspace, the use of different coordination patterns allowed learners navigating between stages of coordination and control to "play" with higher-order derivatives such as the angular speed of rotation of the elbows or knees, even though the patterns led to identical performances. Thus, exploring the relationship among high-order derivatives, coordination patterns, and movement effects through a circular subject-environment relationship promotes coordination flexibility, which is needed to adapt the pattern to a changing environment.

Although a certain strategy emerged concerning the nature of exploratory behavior, our results also showed strong interindividual differences in the exploratory paths. We observed no logical succession in the coordination patterns; for example, ranging from a novice pattern to an expert pattern. Chow et al. (2008) and Hong and Newell (2006b) had already noted no single direction in the qualitative changes that take place during the learning process. Without focusing on the changes over time but rather on the exploration taking place at a given moment in task learning, several authors have highlighted the use of various exploration strategies (King et al., 2012; van der Kamp & Savelsbergh, 1994). Van der Kamp et al. (1994) specifically showed in six-month-old infants that the same individual could exhibit three different strategies depending on the task (Figure 68). In a task where infants had to try to grab balls at equal distances from each other, the left panel shows (a) the path of the infant's left hand (dotted line), which exhibits a local strategy. In contrast, the path of the right hand (solid line) exhibits a non-local strategy (i.e., an anchor and variations around it). The right panel shows (b) the right hand of the same child in the same task, with the exception that he is holding a support board with his left hand; in this condition, the path of the right hand instead defines a blind strategy.

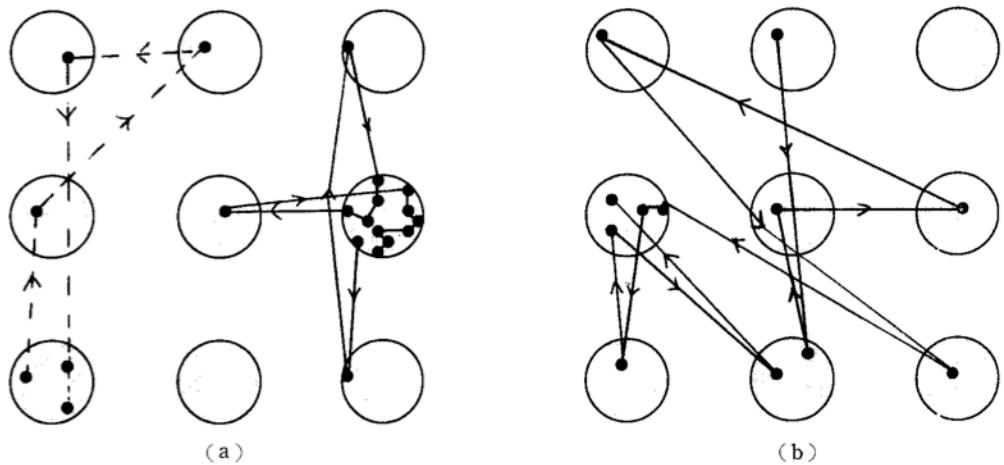


Figure 68. Different exploration strategies exhibited by the same infant when he had to grab a ball located within the circles (left hand in dotted lines and right hand in solid lines).

Again, these divergent results showed the strong dependence of exploration on the interaction of organismic, environmental and task constraints (Newell & Vaillancourt, 2001); it is therefore difficult to generalize about a single exploration strategy. The idea of learning through exploration, with alternating increases and decreases in variability (Berthouze & Lungarella, 2004), was supported by our last study, in which the learner who did not explore (or very little) showed no change in the coordination pattern over practice sessions and, moreover, exhibited the in-phase pattern, indicating novice coordination, over the entire course of sessions.

Instructions as a temporary constraint. The impact of constraints on exploration appears to be highly beneficial in that it can be used to guide exploratory behavior (David et al., 2008; McDonald et al., 1995; Newell, Morris, & Scully, 1985; Newell, 1990). The third study therefore investigated both the effectiveness of adding a temporary task constraint in order to elicit the emergence of a new coordination pattern in learners and the interest of orienting the constraint toward the desired movement form. Without contradicting previous studies focused on movement (e.g., Al-Abood, Bennett, Hernandez, Ashford, & Davids, 2002; Shea & Wulf, 1999; Wulf, Hoess, & Prinz, 1998), the results of this research provided deeper insight into the relationship between the use of an inner focus and the participant's learning stage. Although experts (i.e., a participant in the last stage of learning, "skilled") can be disturbed by the focus on the shape of a movement because their movements have to some extent become automatic, learners situated between the stages of coordination

and control should be able to benefit from a focus on the movement pattern because these stages are very much concerned with the assembly of the pattern (Newell, 1985; Peh et al., 2011). However, guiding learners without constraining them to the use of a defined pattern (i.e., without completely inhibiting the expression of degeneration) implies that the constraint has to provide only partial information about the movement pattern to avoid the risk of prescribing the desired coordination and preventing exploration. In this regard, the results of the fourth study highlighted the observation that prescribing the coordination to be learned, the "target" to be reached, engendered a change in the nature of the exploration that occurred during practice sessions in terms of changes in variability and the stabilization of intermediate patterns. The lack of temporary stability observed in the prescription group may have reflected a lack of exploration. In fact, the exploration/exploitation ratio was greater than 1 in this group, more likely indicating high instability due in great part to the significant competition between the intrinsic dynamics and the pattern to be learned. Prescription thus seems to have led these learners to produce an exploration/exploitation ratio greater than 1, which meant more exploration (i.e., transition from one pattern to another) and less exploitation (i.e., the repetition of the same pattern from one cycle to the other) than other groups. The important question now is whether too much exploration reflects instability rather than actual exploration. In other words, is there an optimal ratio? In contrast, the use of a non-prescriptive constraint focusing (partially) on the shape of the movement was shown to guide the learners' natural exploration, thereby bringing about the use of different coordination patterns during the learning process. In other words, non-prescriptive instructions increased the exploration in this group compared with the control group, while allowing for a certain amount of exploitation of patterns already explored. Logically, the results showed a certain linearity in the relationship between the more or less prescriptive nature of the constraint and the quality of exploration; specifically, the results showed that an additional constraint could encourage exploration, but that the more it provided explicit information and prescribed the coordination, the more it limited exploration. Last, the level of the environmental constraint had a similar impact on exploration and the expression of degeneration, suggesting that the degenerative architecture of neurobiological systems plays an important role in the exploratory nature of motor learning.

Implications for nonlinear pedagogy. Such a non-prescriptive and thus non-deterministic process of guidance does not mean that predictions are impossible about the direction that exploration will take (Davids et al., 2012). It does, however, require

a very detailed knowledge of the effects that constraints have on the emergence of behavior. In fact, the non-prescriptive nature of the constraints-led approach permits learners to adapt to the unique interaction of the constraints affecting them as individuals, and thus each learner is able to discover his or her personal limitations to achieving the task goal (Chow, Davids, Button, et al., 2007). The manipulation of the relevant task constraints provides instructors and coaches with a nonlinear model to shape the emergence of coordination patterns (Chow et al., 2011). In contrast to a linear pedagogy that prescribes the movement to be learned, *nonlinear* pedagogy respects and even enables the use of the degenerative nature of neurobiological systems. In fact, nonlinear pedagogy provides a framework for explaining individual differences in behavior and calls for the respect of these differences in learning programs (Chow et al., 2011). Even though the task and environmental constraints are the same, the learning dynamics are different for each individual because of different organismic constraints (e.g., intelligence, size, strength, etc.). In addition, microscopic changes in a constraint can lead to a reorganization of the macroscopic order parameter, such as an auditory signal leading to a global reorganization of coordination (i.e., sensitivity to initial conditions). However, for the same modified constraint, this reorganization may be different for each learner in the sense that the functional solution emerging from the interaction of constraints is unique and specific to each individual.

CONCLUSION

The application of the concepts and tools of coordination dynamics and ecological psychology in this work has provided deeper insight into the relationship between novice and expert behavior. This relationship reflects a regime of *metastability*, which refers to the co-existence of two tendencies, integration (or the tendency of system elements to act as a coordinated unit) and segregation (or the tendency of system elements to act in isolation) (Kelso & Engström, 2006). Metastability is the main regime by which learners exhibit different coordination patterns during practice sessions, while it also ensures the functionality of these patterns. Metastability thus appears to be a mechanism that promotes the active exploration of the perceptual-motor workspace, which in turn allows the learner to explore the functional relationships between movement and information and to develop a certain flexibility in coordination in response to changes in the practice conditions.

This *exploration* is hybrid or non-local in that it defines periods of relative stability in a coordination pattern, accompanied by a significant period of exploration around this stable pattern. This exploratory process appears to be a series of nonlinear qualitative changes, with learners sometimes returning to "take refuge" in their initial pattern by stabilizing it once again after having left it; this may even occur quite late in the learning process. The successive stabilization of distinct coordination patterns reflects the expression of the multipotentiality of *degenerative neurobiological* systems; that is, the same set of elements (i.e., here biomechanical degrees of freedom) can organize and reorganize differently, sometimes involving additional degrees of freedom, in order to ensure the continuous functional equivalence of the system and, ultimately, energy efficiency, whatever the constraints acting on the individual.

Last, the exploration exhibited by learners is greatly dependent on the interaction of task, environmental and organismic constraints (Newell & Vaillancourt, 2001). This dependency restricts the potential for exploration to a certain extent by limiting the expression of the degenerative nature of neurobiological systems when the impact of constraints increases. On the other hand, however, this allows for setting limits on exploratory behavior by modifying task constraints and hence the practice conditions. In fact, we found that as long as the temporary additional constraints

provided implicit information but did not prescribe a specific pattern to be learned, learners' exploration strategies were modified mainly toward an increase in the exploration of viable possibilities as opposed to a completely open-ended practice.

This work ultimately proposes a new perspective for professionals in sport and physical education through nonlinear pedagogy. Nonlinear pedagogy does not mean that learners should be left to explore on their own, finding motor solutions that seem appropriate to them. Instead, instructors and educators should facilitate their search for new solutions by creating environments for practice that set limits on exploratory behavior (Brymer & Renshaw, 2010). Such an approach requires processes like task simplification rather than the decomposition of tasks into subtasks followed by recomposition (Davids et al., 2008). Nonlinear pedagogy thus seems to provide appropriate support for the development of both stability in the pattern being learned and the flexibility needed to respond to the dynamic interaction of task, environmental and organismic constraints.

One perspective suggested by this study of the temporal dynamics of coordination would be the nonlinear modelling of oscillators, along the lines of the work from Nourrit et al. (2003). This work has already begun, and the aquatic environment seems to have yielded results in contradiction to those of Nourrit et al. (2003), which is primarily that the behavior of expert swimmers should conform to the Rayleigh model (i.e., defining variations in oscillation speed within a cycle). Also, it would be interesting to further investigate the use of temporary informational constraints during the learning process, with a focus on the notion of an optimal exploitation/exploration ratio. To do so, greater insight into the potential for exploration offered by prescription would first be needed.

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APPENDICES

Annex A: validation of body sensor unit measurements

Annex B: Paper accepted or under revision

Annex C: Individual data of stroke length for each group and each speed condition.

Annex D: 3-D histograms of each participant showing the occurrence of transitions between patterns (height of bars) and the time of appearance during the practice (colour of bars)

Annex E: Individual data for the Cauchy Index of elbow oscillators, Cauchy Index of knee oscillators, patterns of coordination and Cauchy Index of the CRP, stroke length, switching ratio and stability regime (grey zones correspond to free practice (trials 1 and 2) and white zones correspond to constrained practice (trials 3-10); sessions are separated by the dotted line).

All appendices are available online:

<https://ent.unr-runn.fr/filex/get?k=JdsdHUfKHrKBwat6RHu>

Annex A: Validation of body sensor unit measurements

In order to validate the measurements done with the body sensor units, a comparison was performed on the same movements between sensors angle measurements (Asensors) and Vicon angle measurement (Avicon) (21 cameras, Oxford Metrics, Oxford, UK). The studied movement consisted in a flexion-extension motion in 2D using a compass of two arms of 40cm each (with both arms moving). Three reflective landmarks have been used for Vicon system and were fixed at the extremity of each arm and at the centre of rotation. Two small inertial centrals, combining 3D gyroscope (1600°/s), 3D accelerometer (+/-8G) and 3D magnetometer (MotionPod3, Movea©, Grenoble, France) have been used; each sensor was fixed in each arm of the compass. MotionPod sensors allowed either local or North magnetic references. Both systems were used at 100 Hz sample frequency and were synchronized and piloted with RTMaps (Intempora S.A., 2000, <http://www.intempora.com/rtmaps4/rtmaps-software/overview.html>), so that time-series have similar duration.

Three conditions were tested in order to represent the possible movements performed during swimming:

- i) Relatively slow motion, with different pause leading to angular plateau during reversal points and in the middle of the flexion and extension motions (i.e. associated to the glide phase during swimming)
- ii) Relatively slow motion without a plateau (i.e. associated to the novice pattern at the beginning of the learning process)
- iii) Relatively rapid motion without a plateau (i.e. associated with high swimming speed at the beginning of the learning process). The duration of this condition was intentionally long (i.e. 61 cycles during more than five minutes), in order to assess any possible drift with time.

A twofold approach has been used to estimate the validity of the angular measurements computed from the body sensor signal (Dadashi, Crettenand, Millet, & Aminian, 2012). In the first step, a Spearman's rank correlation was used to verify the association between the measurements derived from the two systems. Then, the agreement between the two systems in angle measurement was assessed by the use of a Bland-Altman plot (Bland & Altman, 1986; Bland, 1986).

In the second step, we investigated the mean accuracy of the sensors in measuring angles by using the root mean squared (RMS) between angles from both measurement systems. Then, the normalized pairwise variability index (*nPVI*) (Sandnes & Jian, 2004) was also calculated following Equation (10):

$$nPVI = 100\% \times \left[\sum_{C_k=1}^N \frac{|A_{sensors} - A_{vicon}|}{(A_{sensors} + A_{vicon}) / 2} \right] / N \quad [10]$$

Where C_k is the k measure realized by both materials, and N is the total number of measures. The Bland-Altman plot was inspected with correlation exploration for existence of heteroscedasticity (Atkinson & Nevill, 1998). Results are presented in Figures 72 and 73 and Table 27.

Table 27. Index of association, agreement and accuracy in the three tested conditions

Variables	Condition 1		Condition 2		Condition 3	
	Slow motion with plateau	slow motion without plateau			rapid motion	
RMS (°)	0.95		2.12		3.40	
<i>nPVI</i> (% of mean value)	2.11		2.69		2.96	
correlation	$p < .001$	$r = .999$	$p < .001$	$r = .997$	$p < .001$	$r = .993$
correlation (heteroscedasticity)	$p < .001$	$r = -.199$	N.S.	$r = 0.03$	N.S.	$r = 0.01$
Percentage of measures outside the confidence interval	1.28		3.05		3.86	

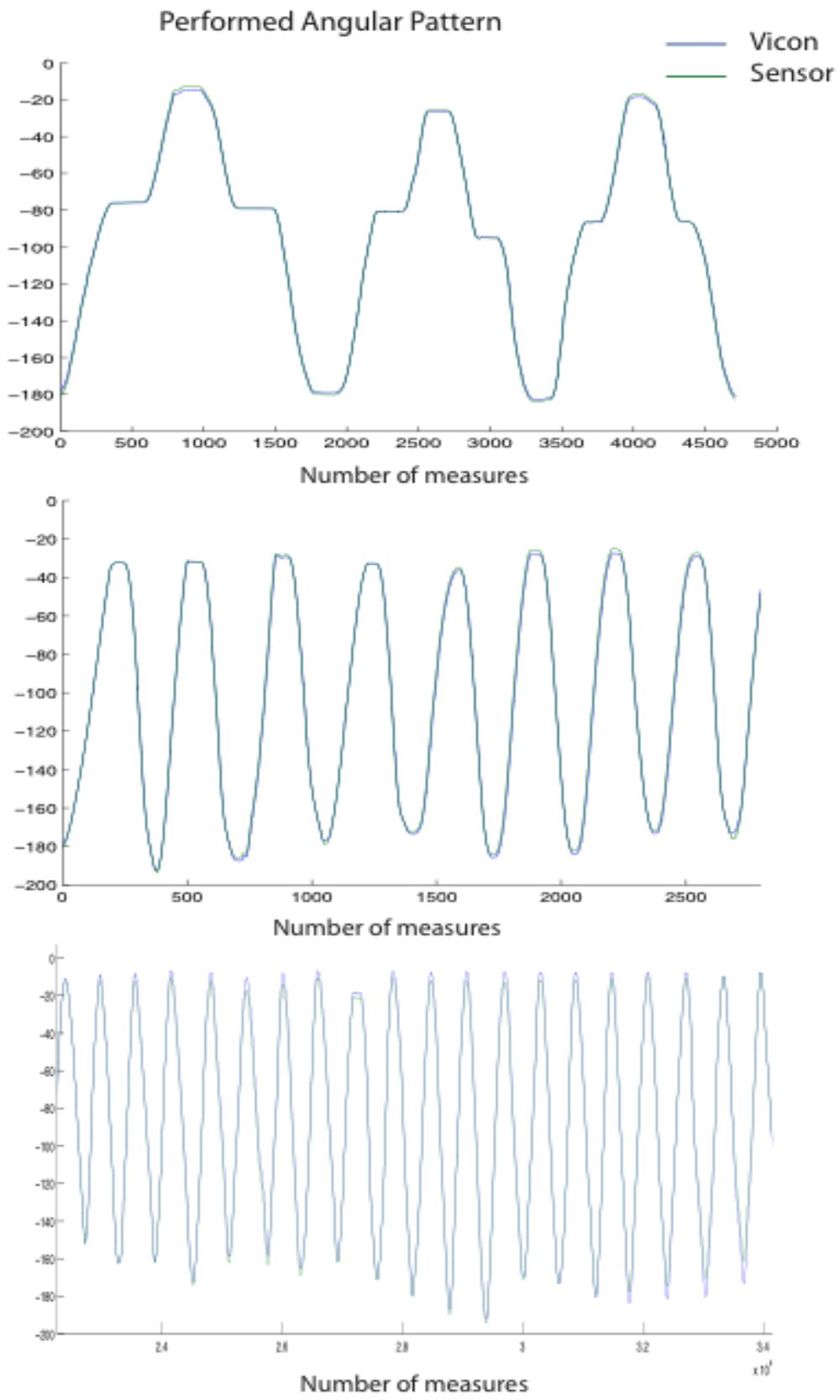


Figure 73. Angular patterns for the 3 conditions: i) top, ii) middle, iii) bottom (note that the angular patterns of the third condition only represent a part of the total amount of cycles performed).

Bland & Altman Plot

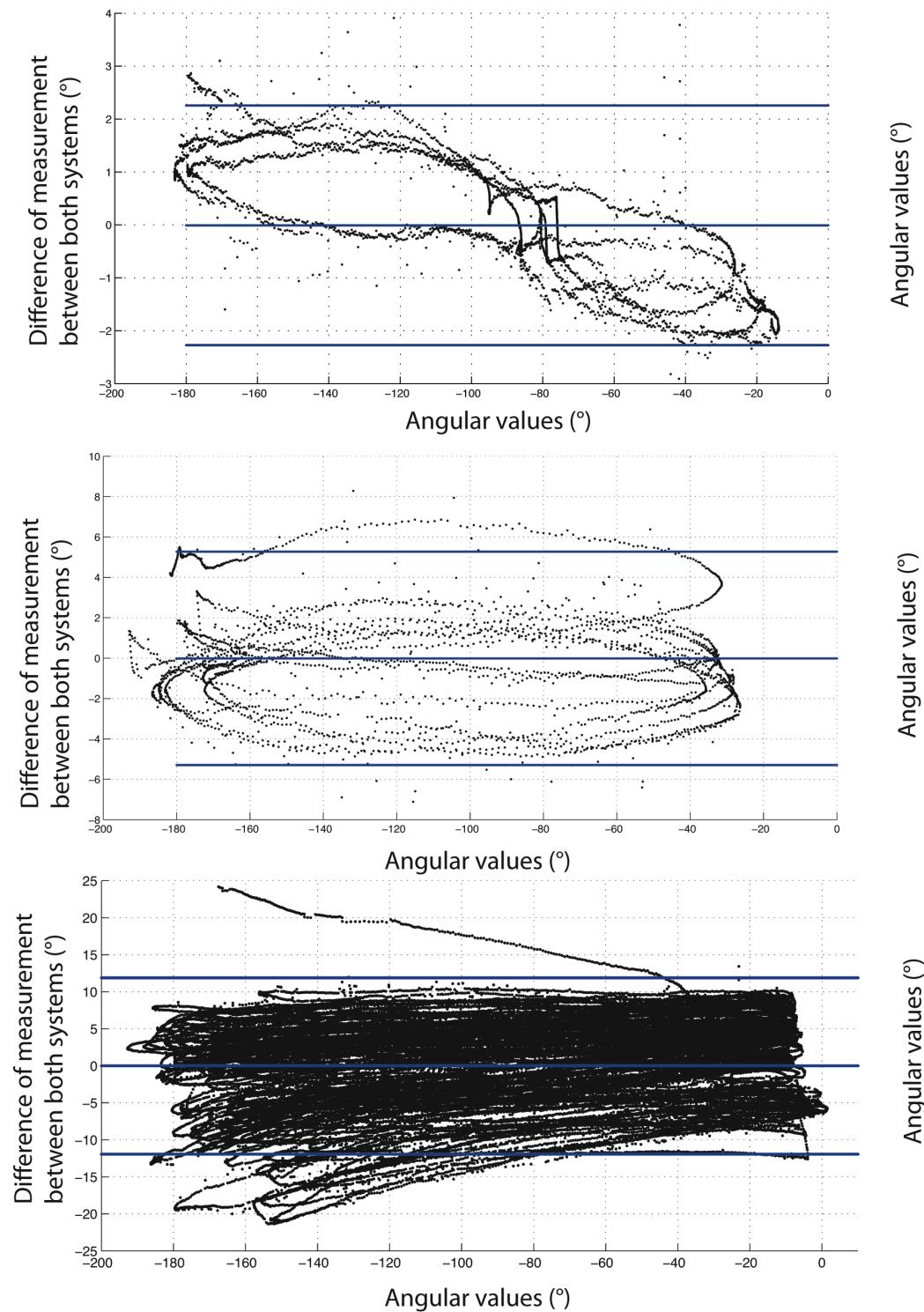


Figure 72. Bland & Altman plots for the 3 conditions: i) top, ii) middle, iii) bottom.

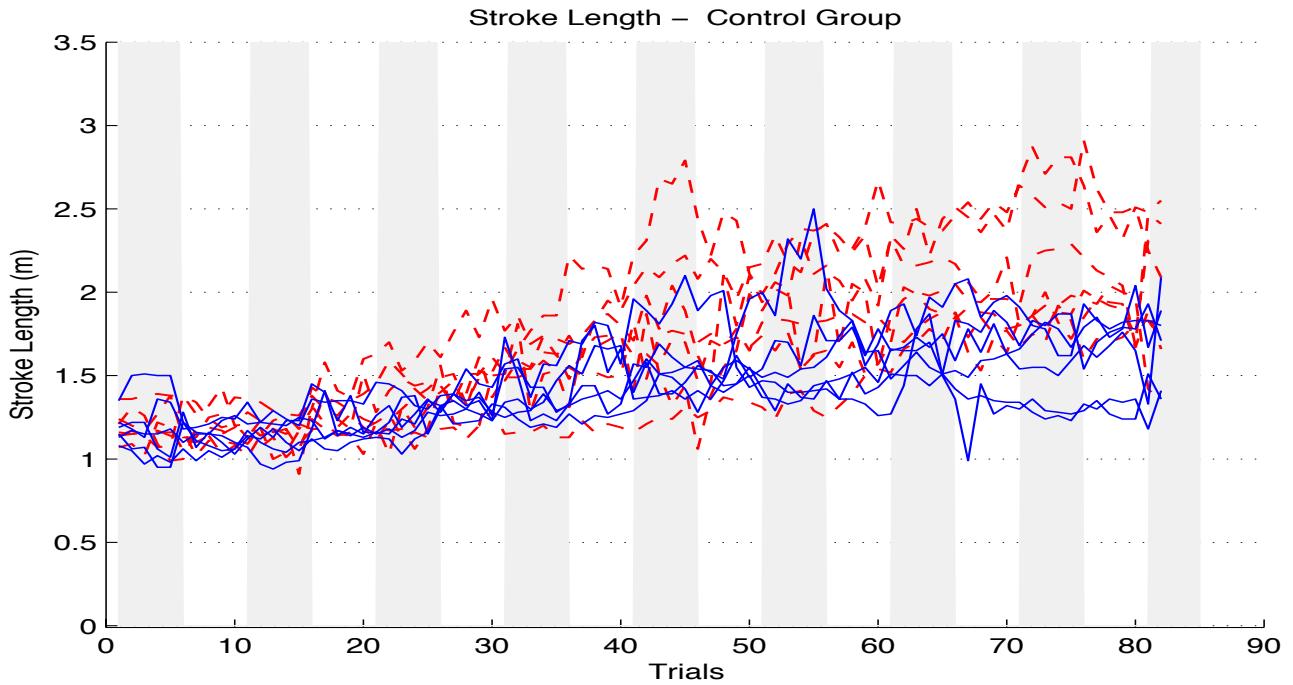
All the correlations between the measurement tools appeared significant and the Bland-Altman plots appeared suitable during the three tested conditions with less than 3.05 percent of measures that appeared outside the confidence interval.

Identically, the RMS and the *nPVI* showed adequately low values comparatively to the literature (e.g., Dadashi, Crettenand, Millet, & Aminian, 2012). Nevertheless, a significant correlation between angular value and differences between the two measurement systems appeared in the condition with plateau, highlighting a possibility of heteroscedasticity (Atkinson & Nevill, 1998). Therefore, the validity of the angular values, especially in the low swimming speed condition, may be valid only in the considered interval (i.e., [17 - 180] $^{\circ}$), which fits well the range of value we assess in elbow and knee oscillations.

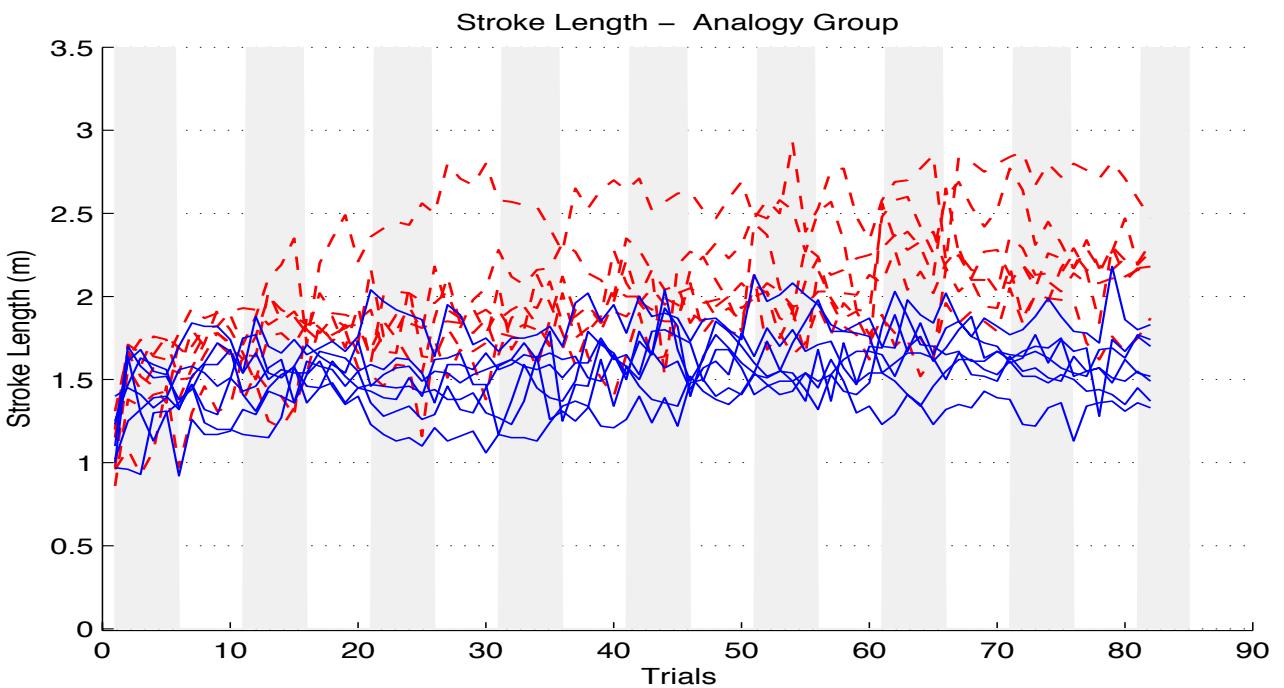
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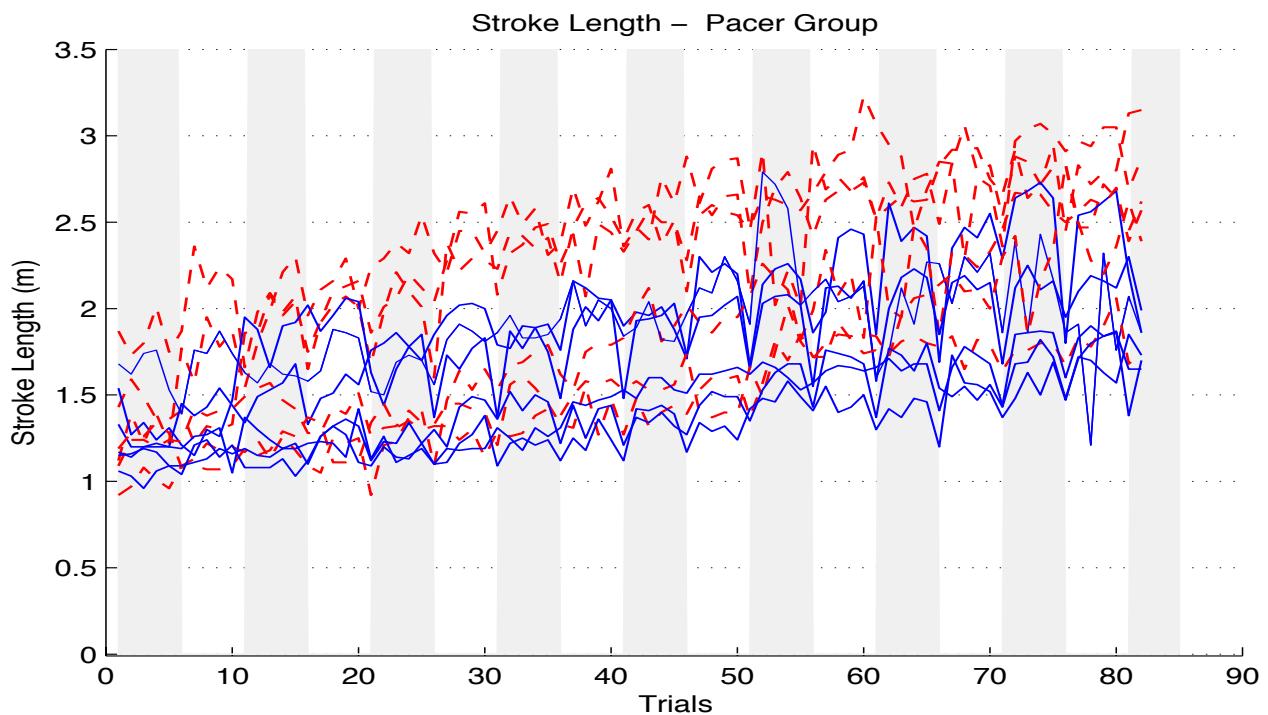
ANNEX C : Individual data of stroke length for each group and each speed condition.



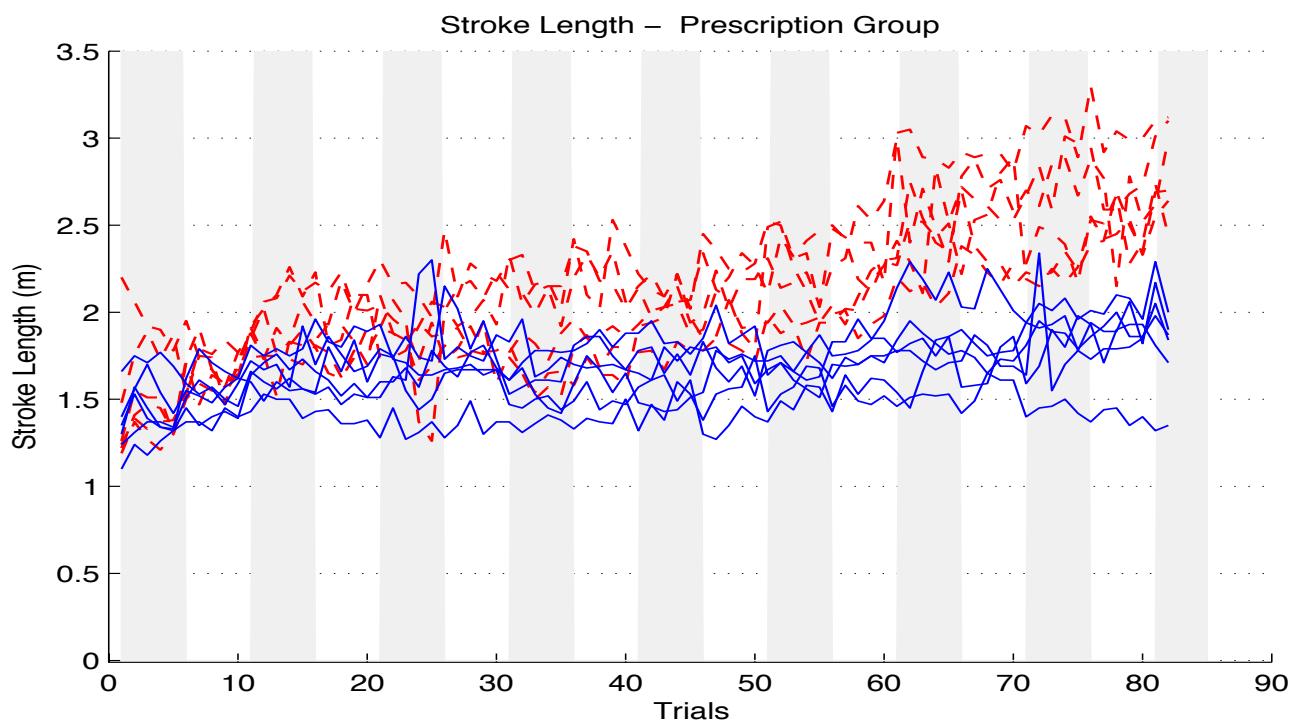
*Mean Stroke Length during each trial for the **Control Group** at high swimming speed (continuous lines) and low swimming speed (dashed lines) (each change in background color represents a new session).*



*Mean Stroke Length during each trial for the **Analogy Group** at high swimming speed (continuous lines) and low swimming speed (dashed lines) (each change in background color represents a new session).*

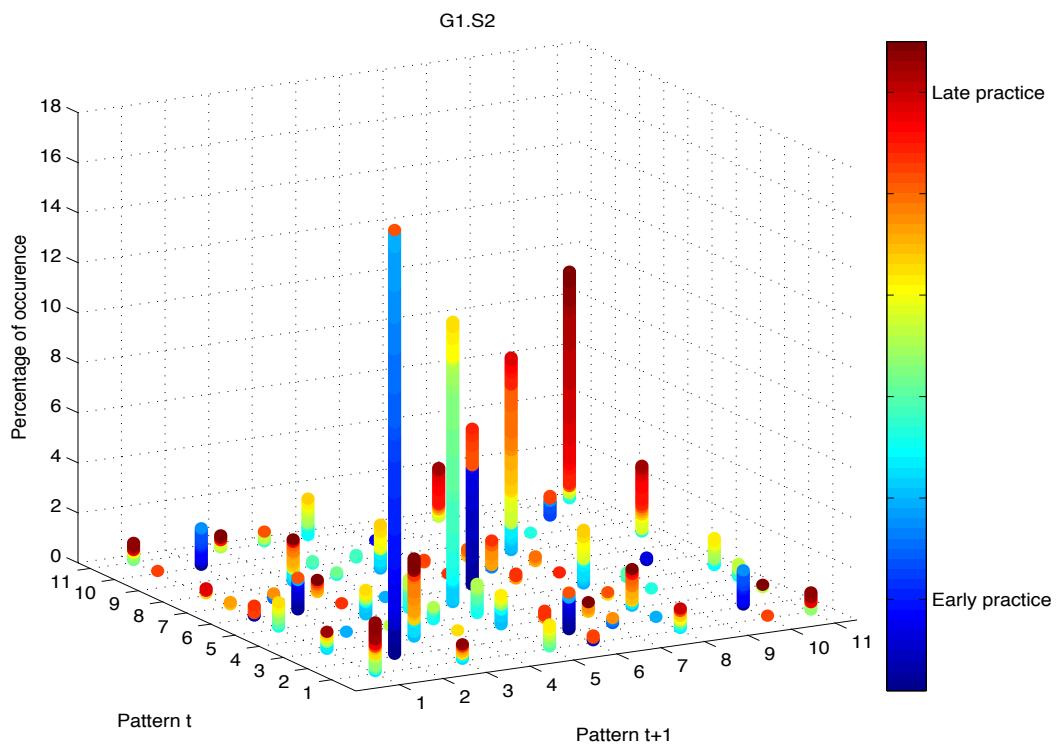
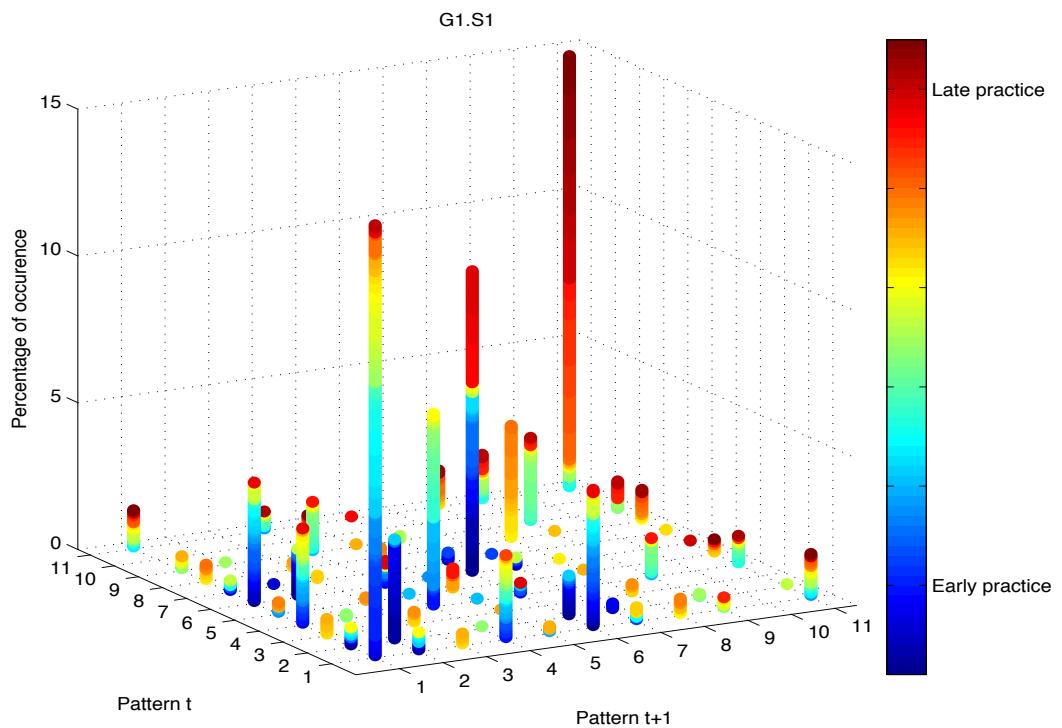


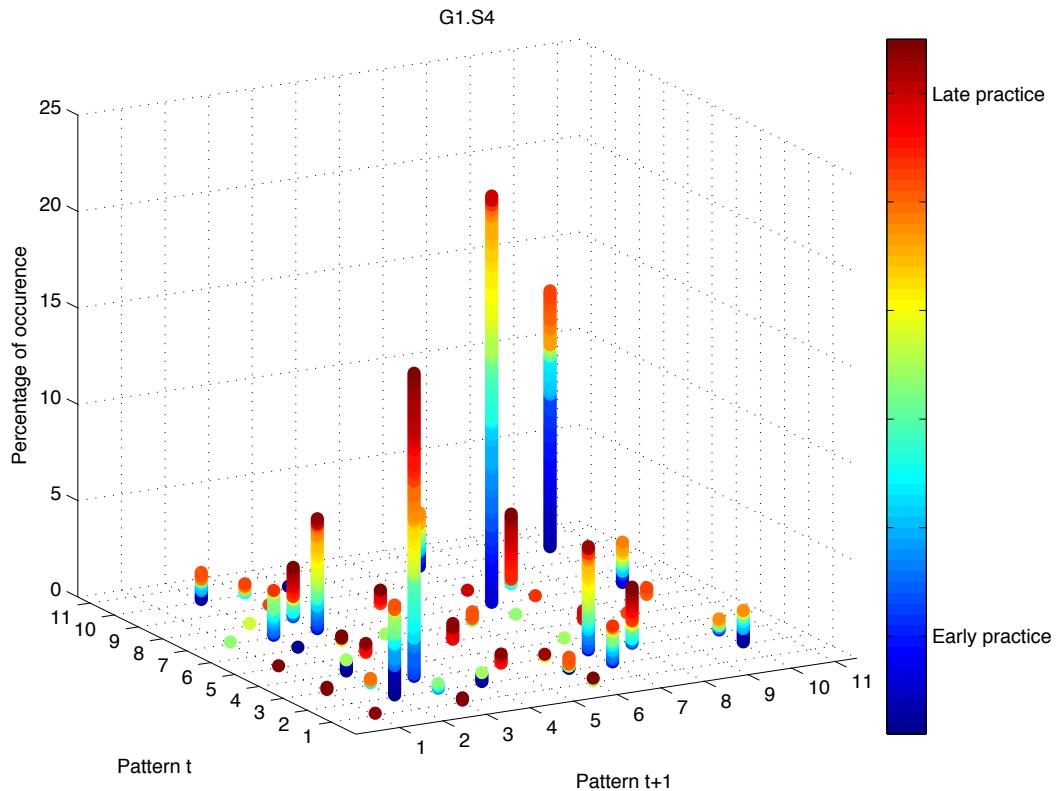
*Mean Stroke Length during each trial for the **Pacer Group** at high swimming speed (continuous lines) and low swimming speed (dashed lines) (each change in background color represents a new session).*



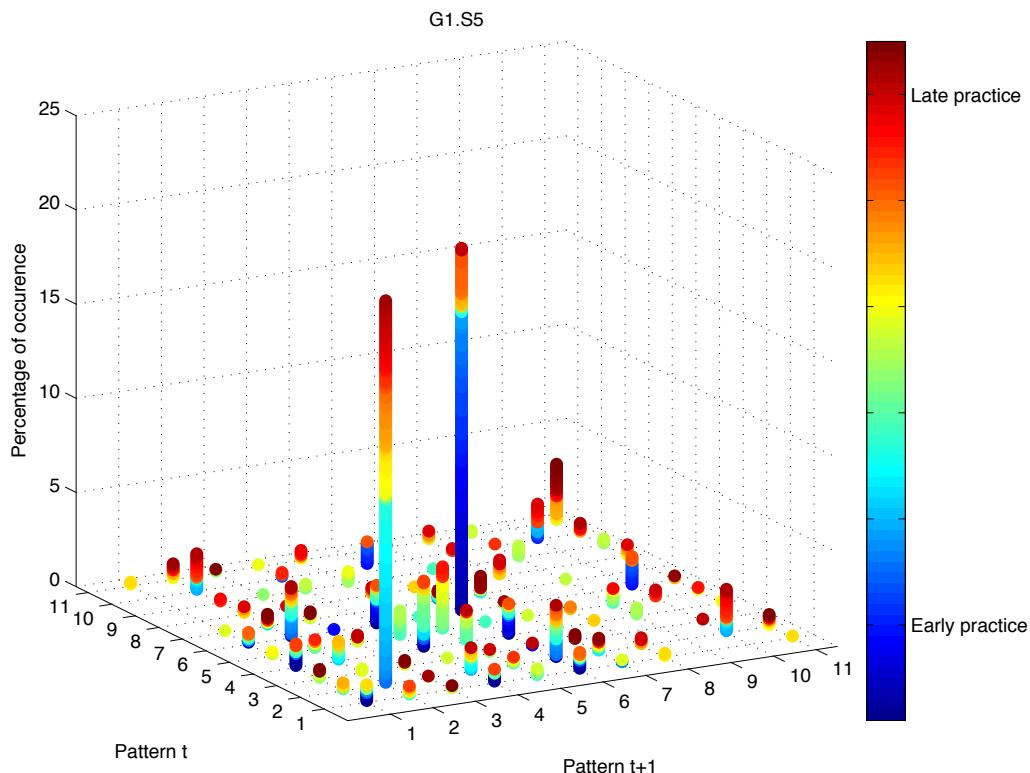
*Mean Stroke Length during each trial for the **Prescription Group** at high swimming speed (continuous lines) and low swimming speed (dashed lines) (each change in background color represents a new session).*

ANNEX D: 3-D histograms of each participant showing the occurrence of transitions between patterns (height of bars) and the time of appearance during the practice (colour of bars)

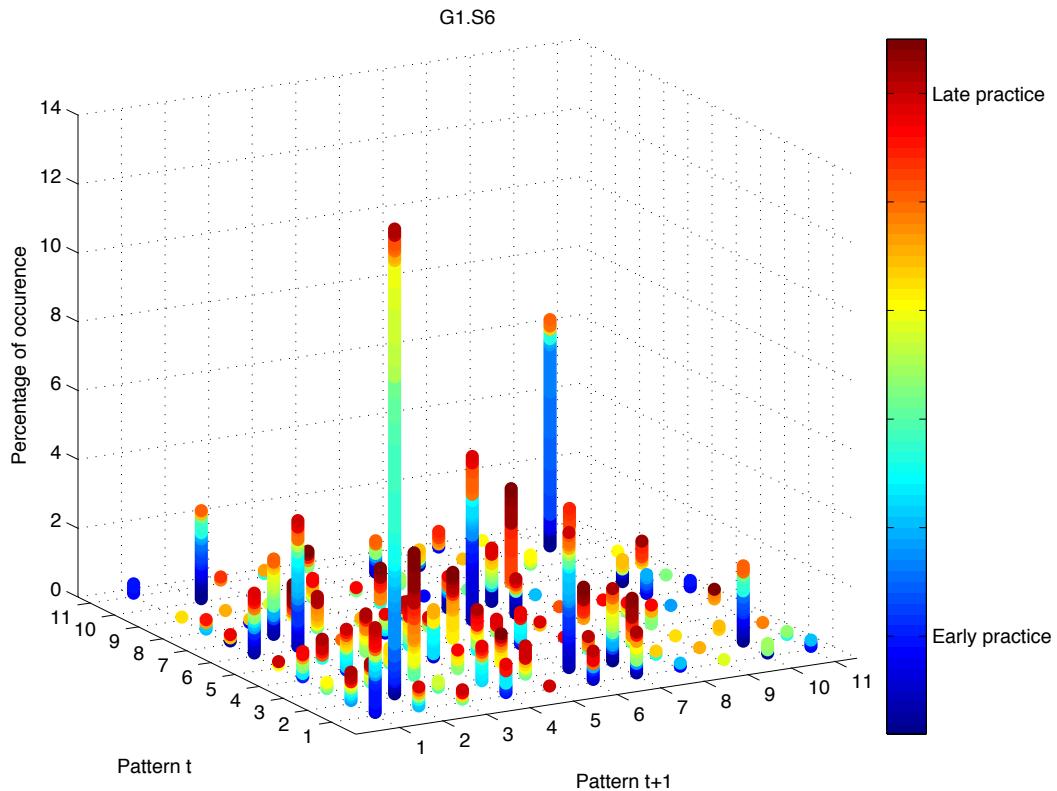




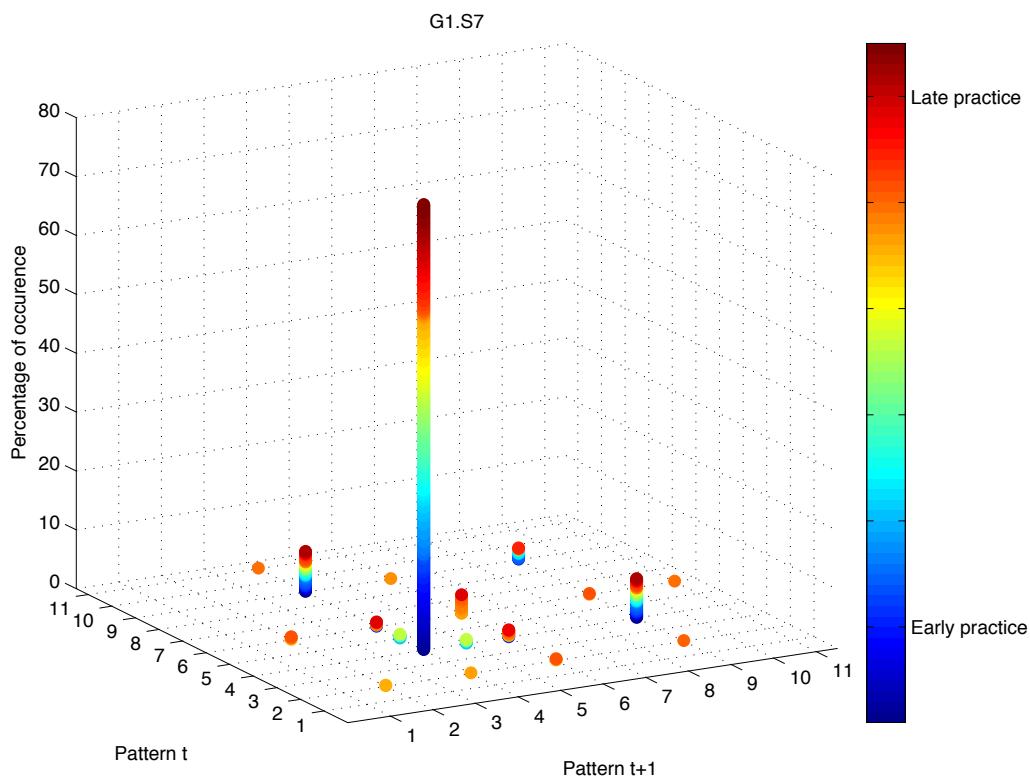
*Percentage of occurrence of transitions between cluster t (y-axis) and cluster $t + 1$ (x-axis) with regards to the time of occurrence during practice (color scale): **Control Group Subject 4***



*Percentage of occurrence of transitions between cluster t (y-axis) and cluster $t + 1$ (x-axis) with regards to the time of occurrence during practice (color scale): **Control Group Subject 5***

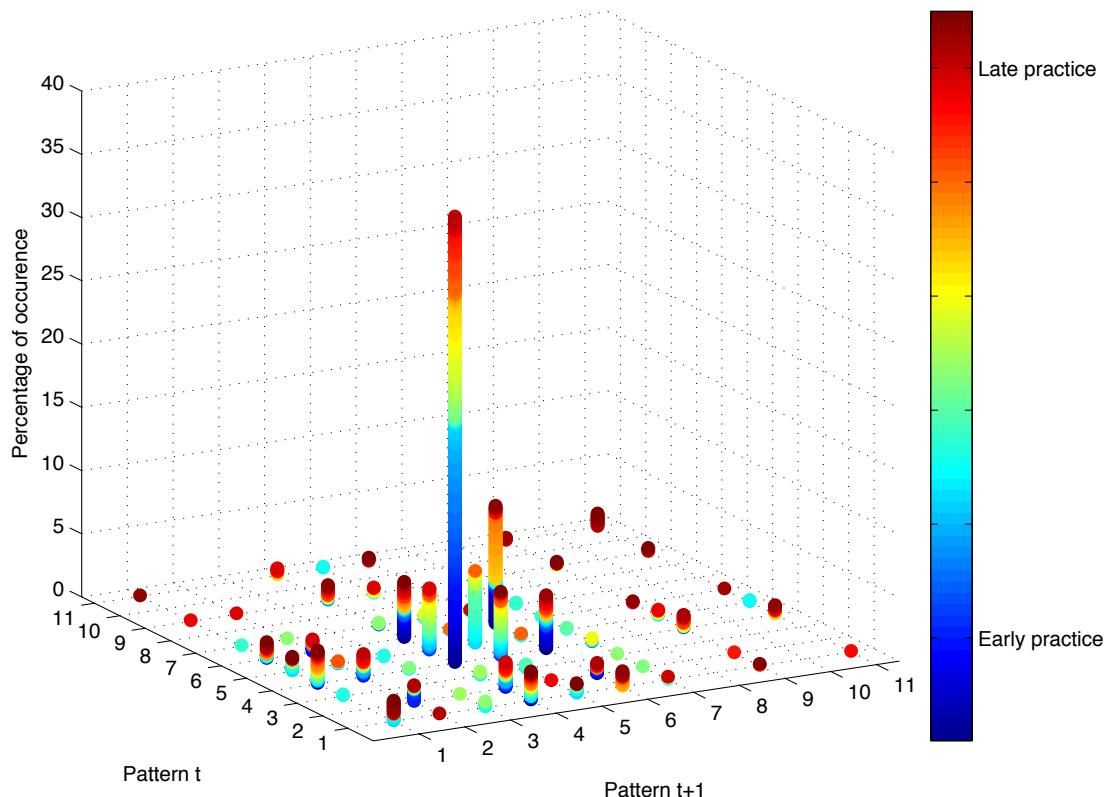


*Percentage of occurrence of transitions between cluster t (y-axis) and cluster $t + 1$ (x-axis) with regards to the time of occurrence during practice (color scale): **Control Group Subject 6***

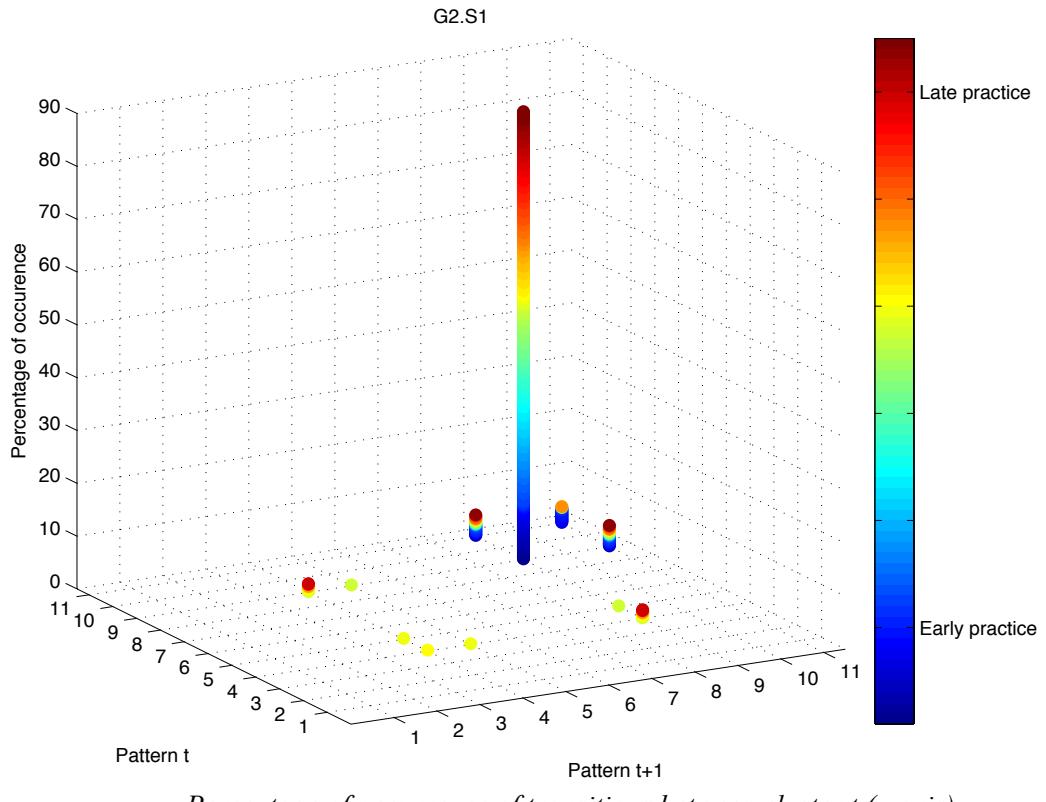


*Percentage of occurrence of transitions between cluster t (y-axis) and cluster $t + 1$ (x-axis) with regards to the time of occurrence during practice (color scale): **Control Group Subject 7***

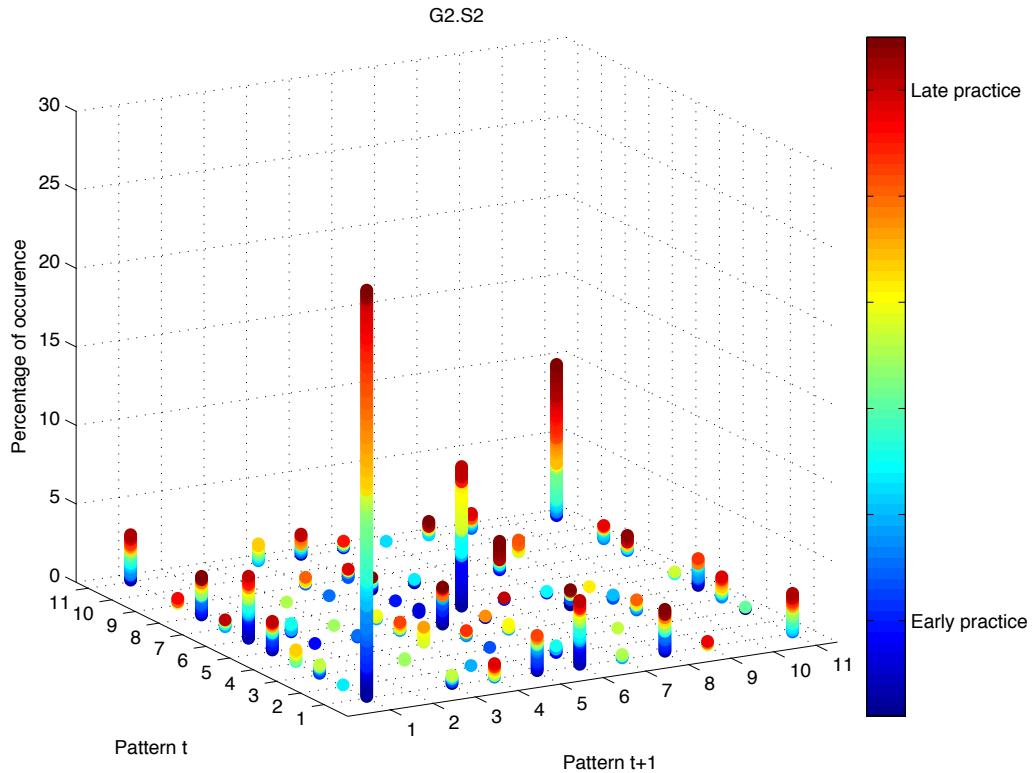
G1.S8



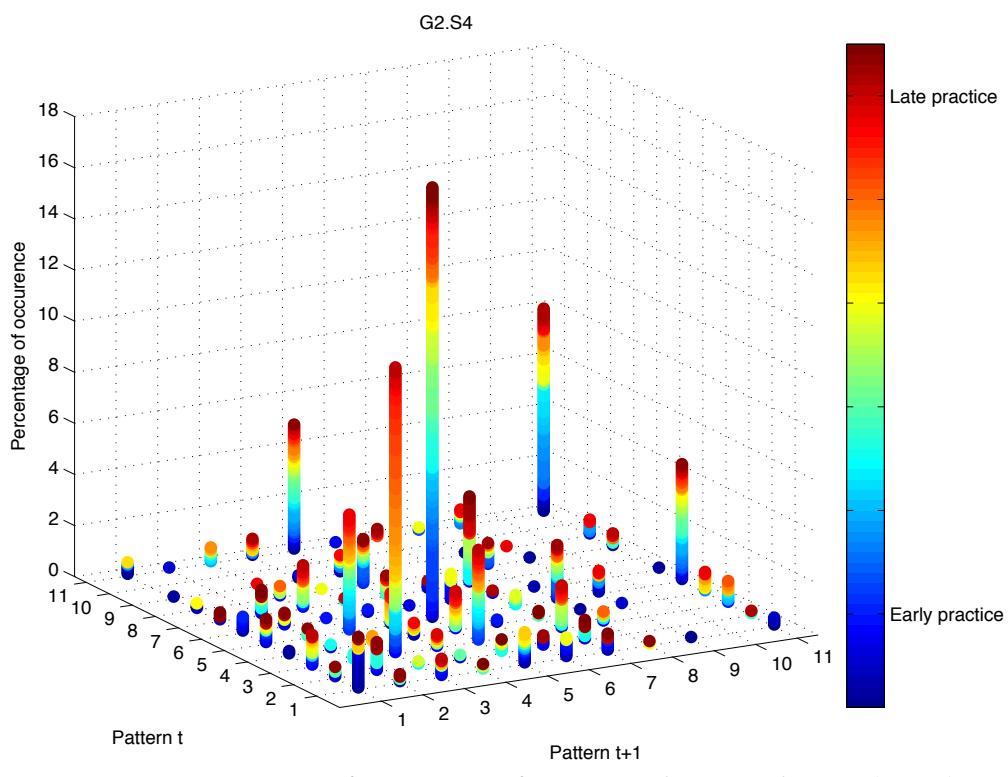
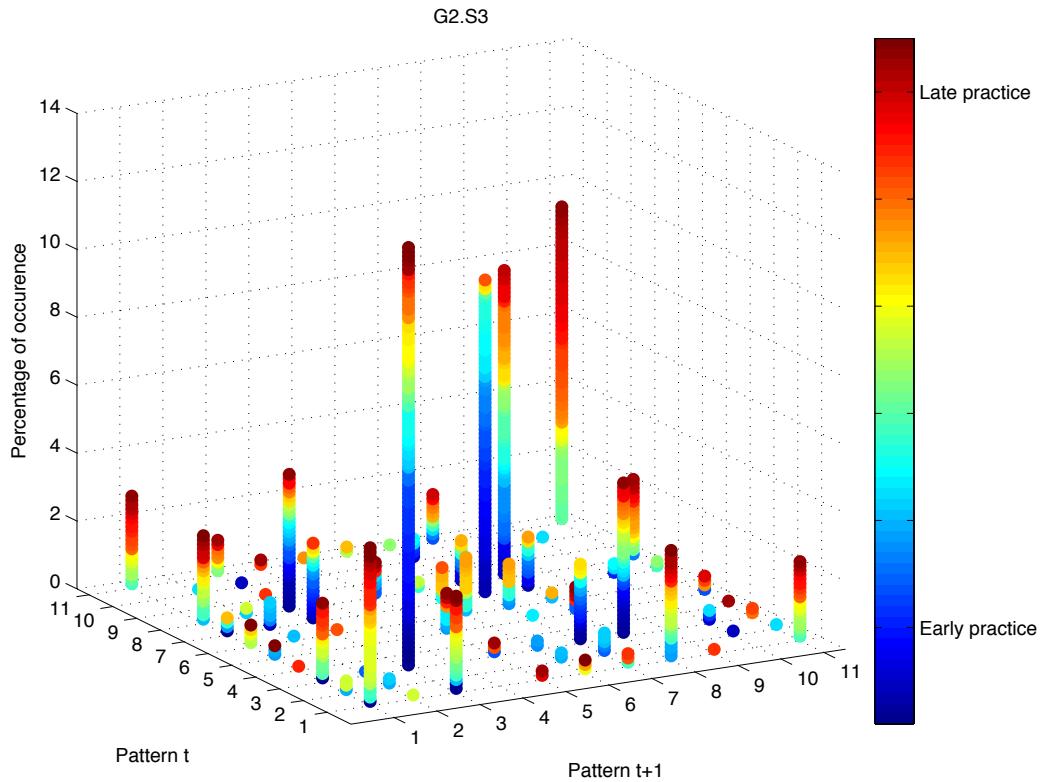
*Percentage of occurrence of transitions between cluster t (y-axis) and cluster $t+1$ (x-axis) with regards to the time of occurrence during practice (color scale): **Control Group Subject 8***

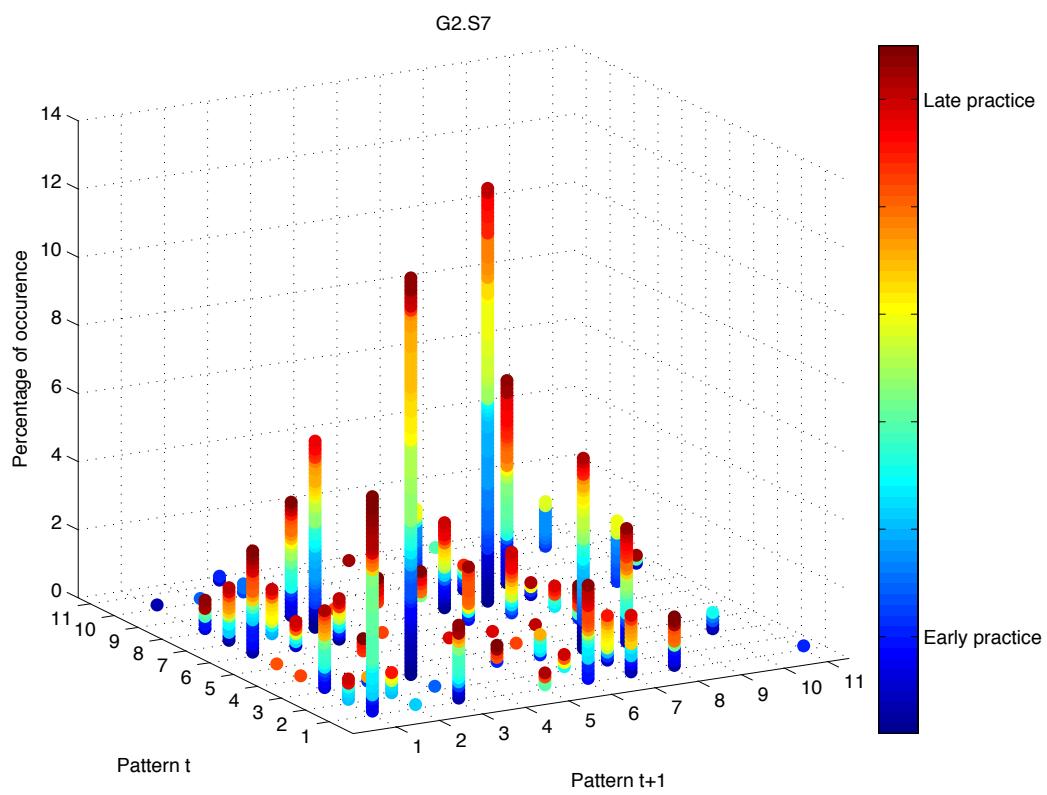
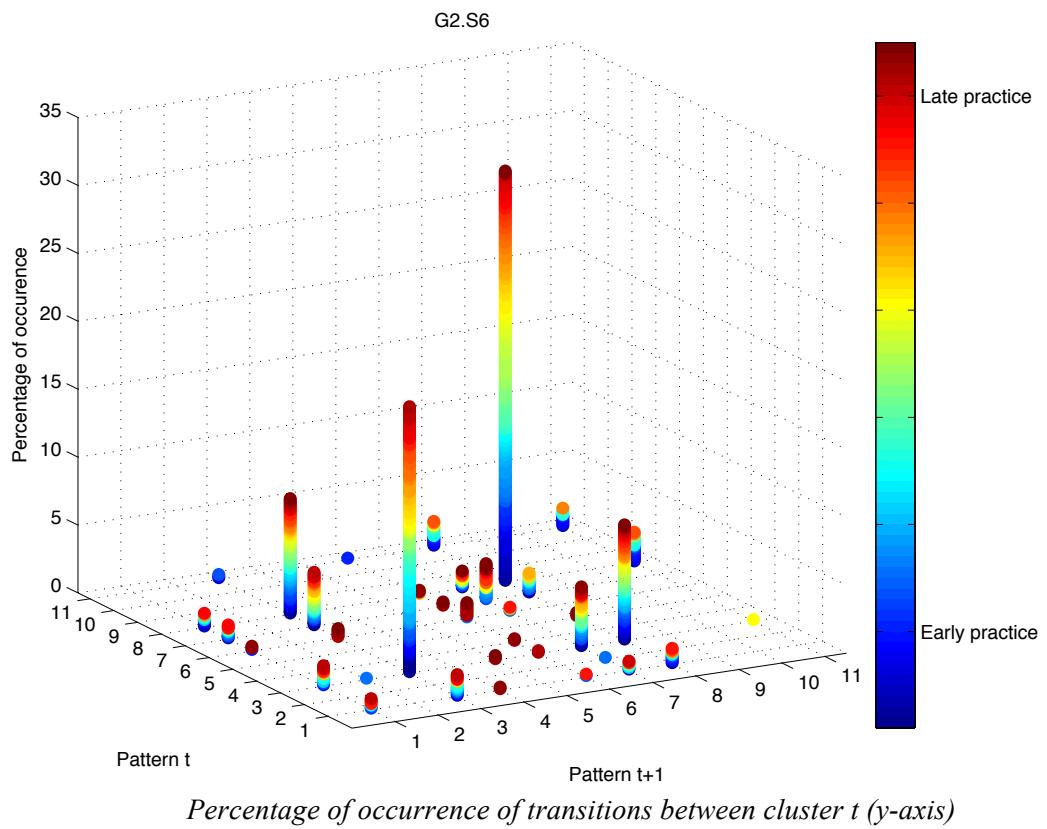


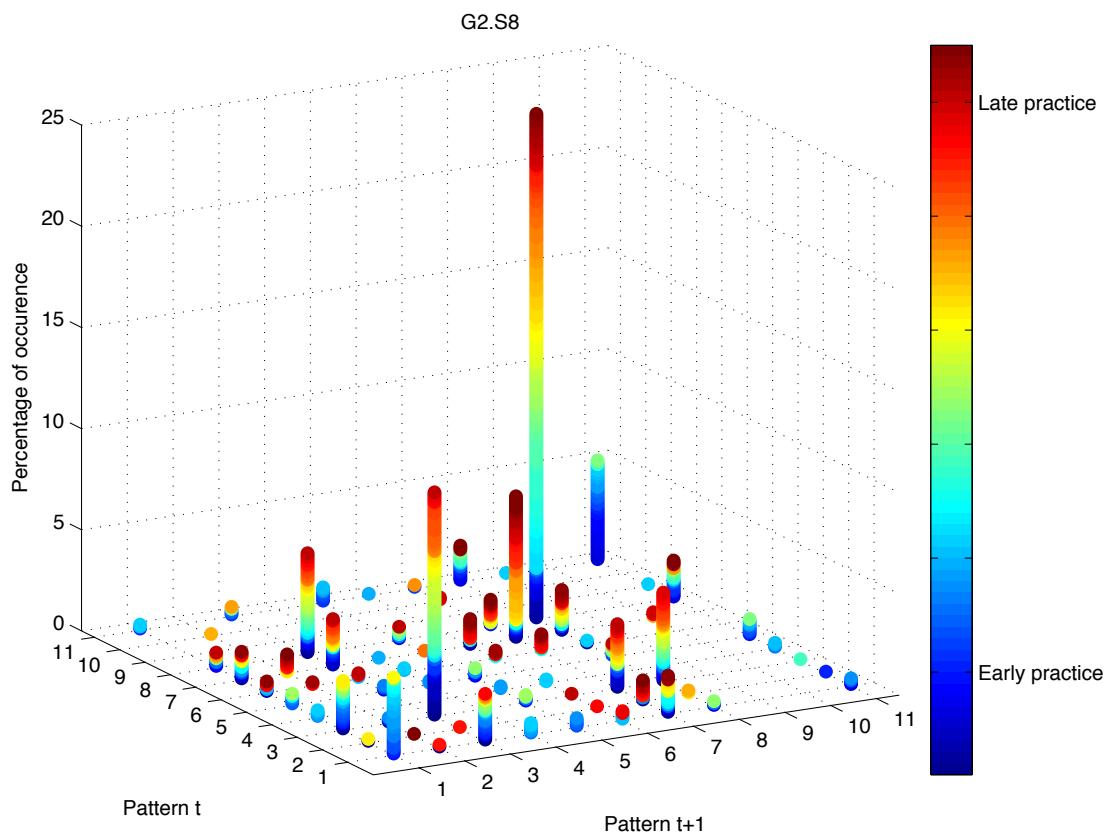
*Percentage of occurrence of transitions between cluster t (y-axis) and cluster t + 1 (x-axis) with regards to the time of occurrence during practice (color scale): **Analogy Group Subject 1***



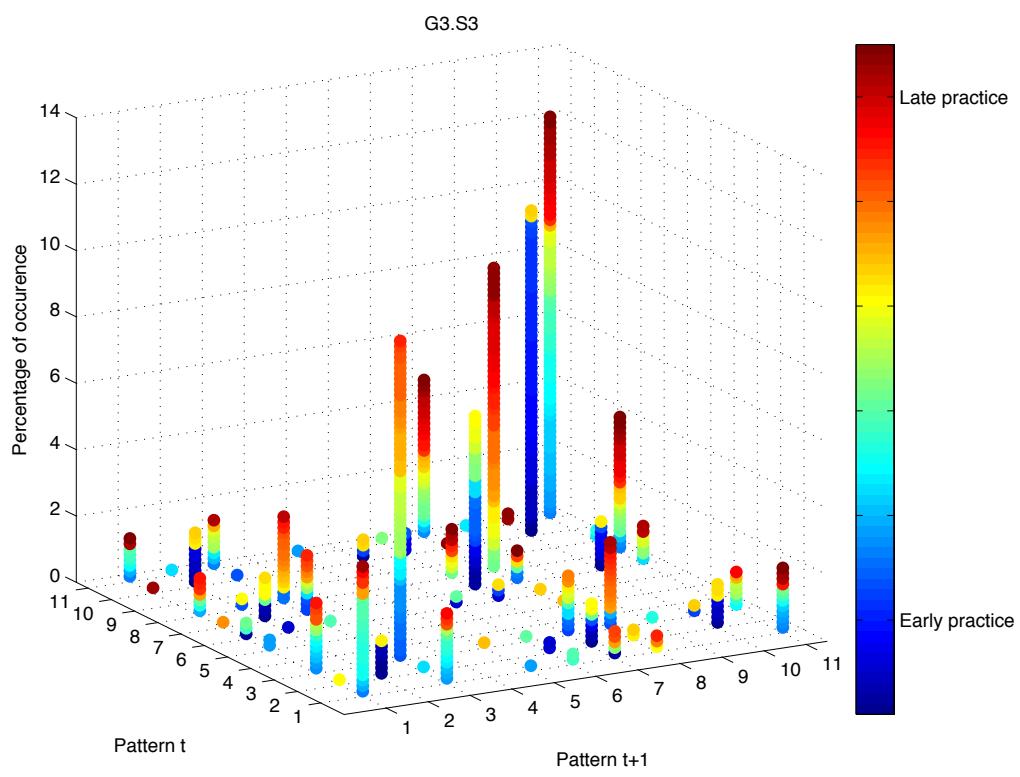
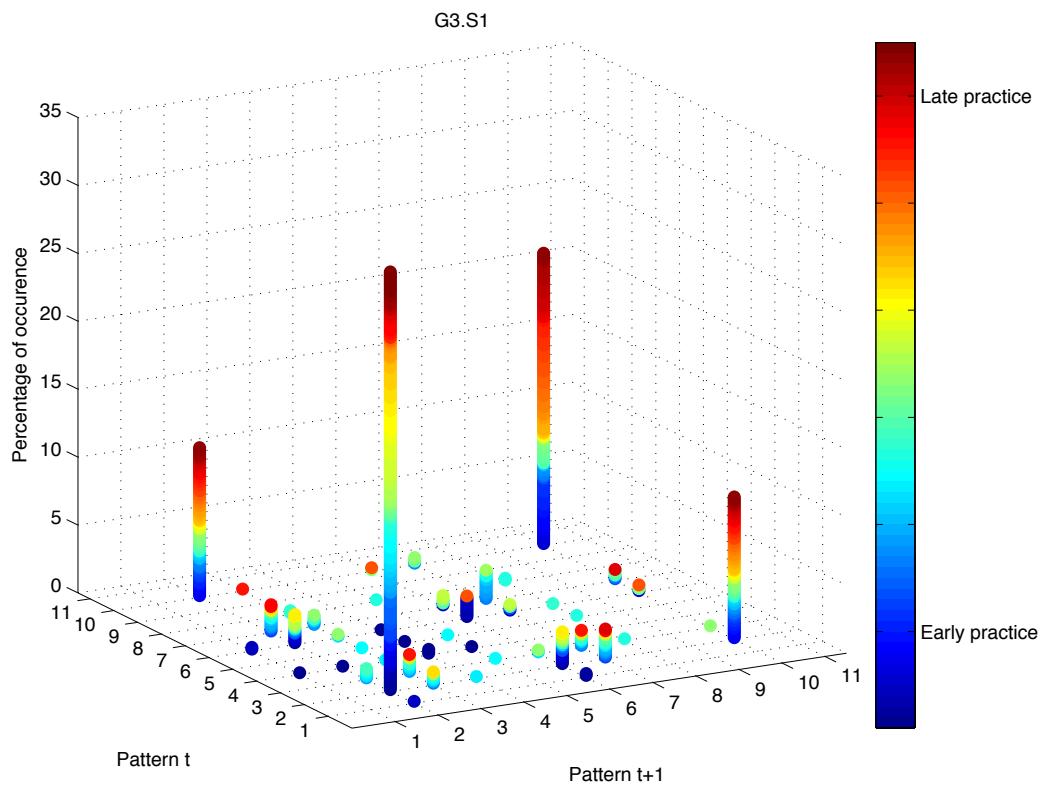
*Percentage of occurrence of transitions between cluster t (y-axis) and cluster t + 1 (x-axis) with regards to the time of occurrence during practice (color scale): **Analogy Group Subject 2***

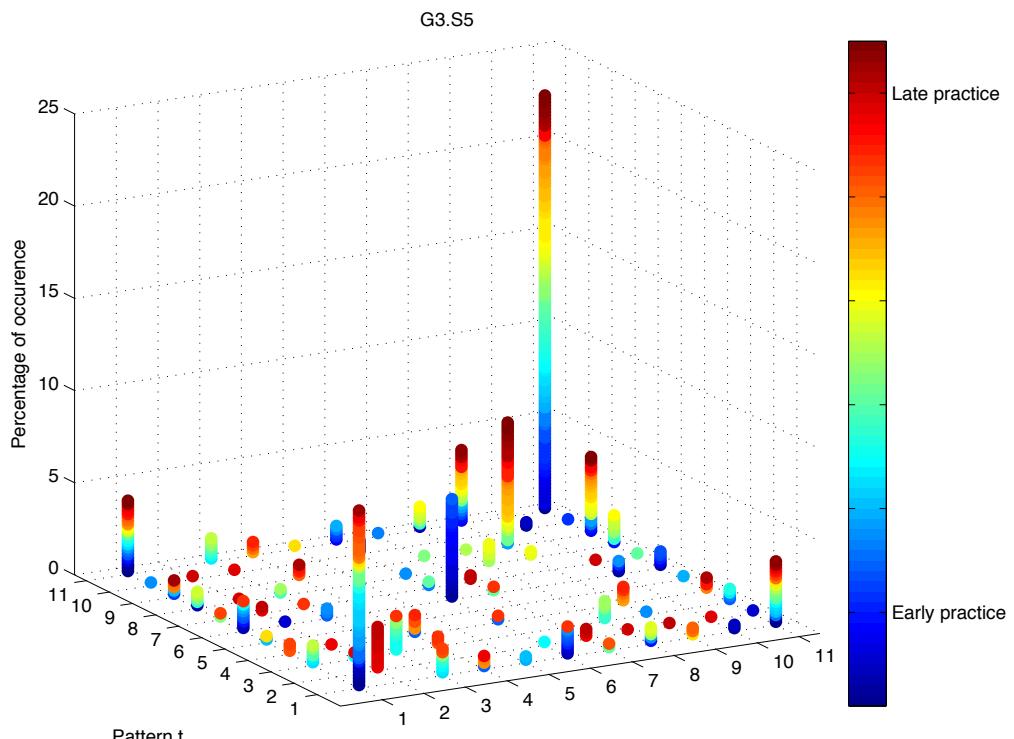




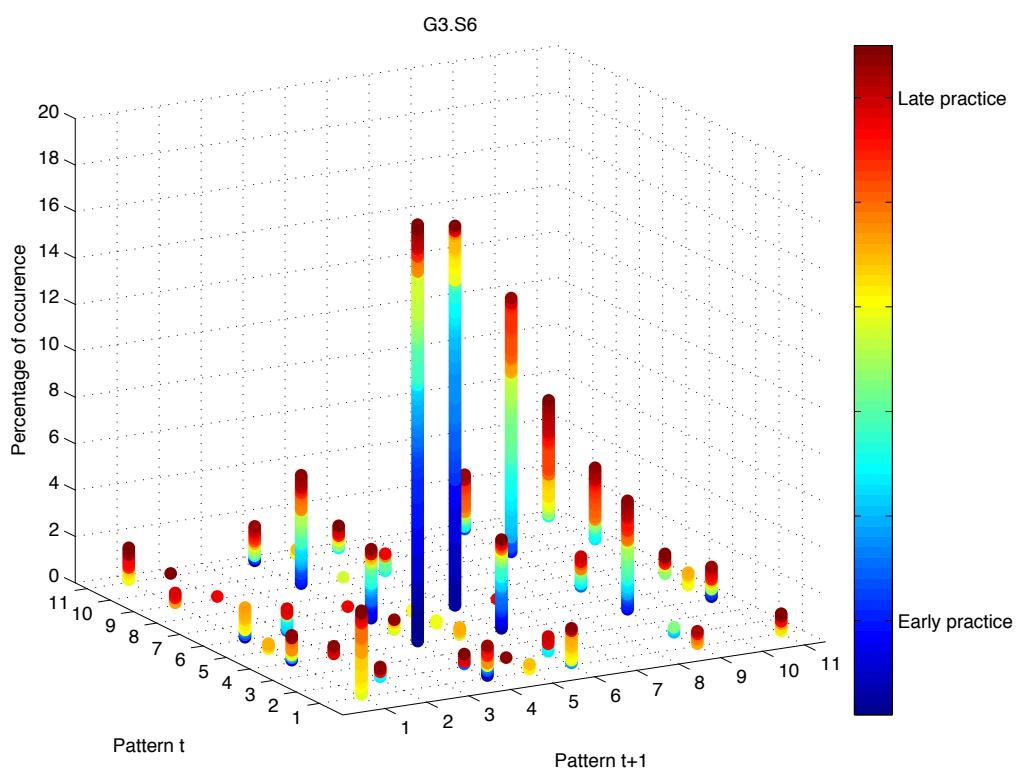


*Percentage of occurrence of transitions between cluster t (y-axis) and cluster $t + 1$ (x-axis) with regards to the time of occurrence during practice (color scale): **Analogy Group Subject 8***

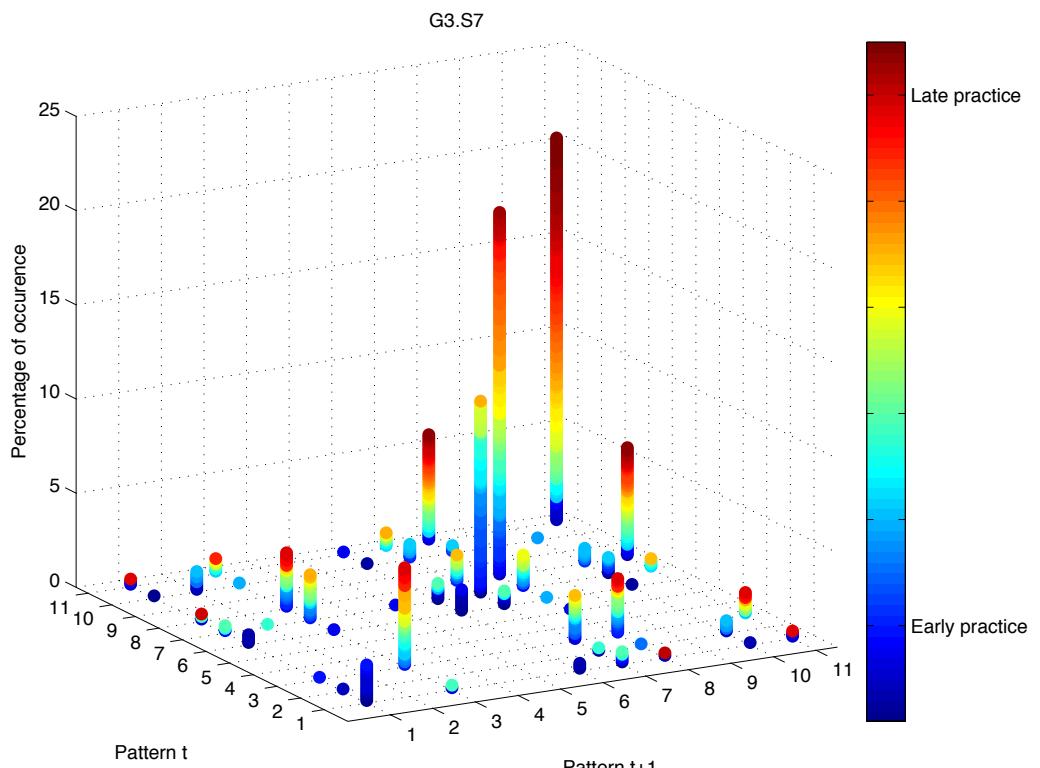




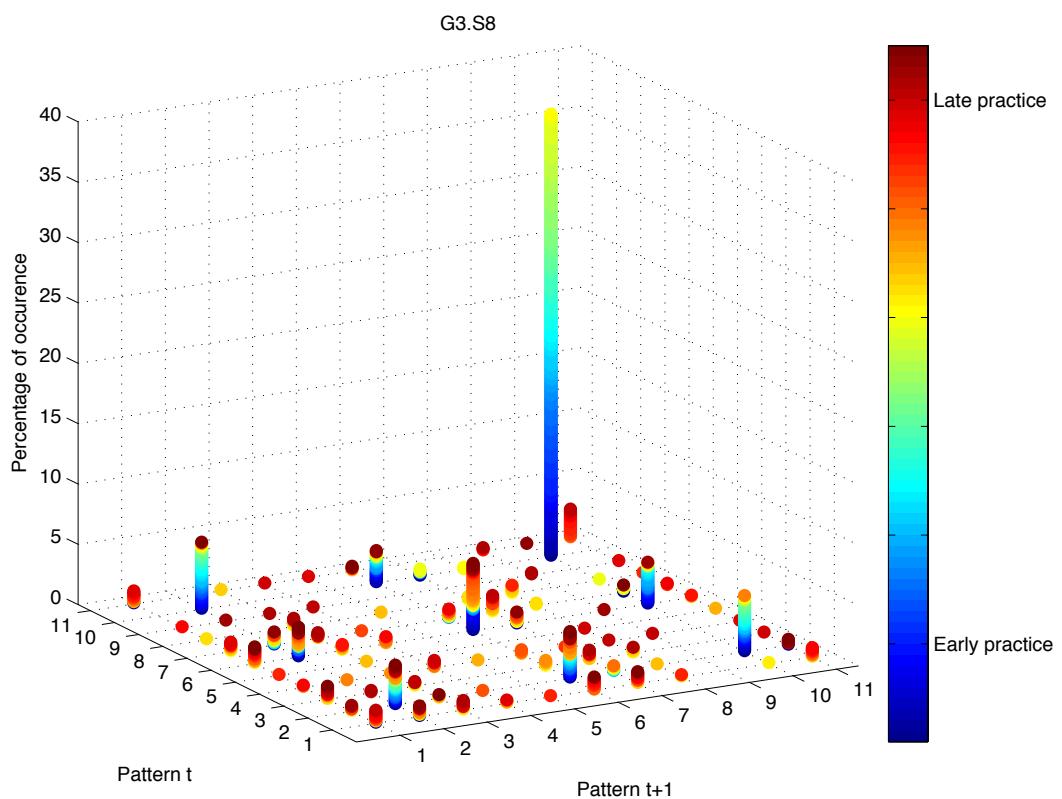
*Percentage of occurrence of transitions between cluster t (y-axis) and cluster $t + 1$ (x-axis) with regards to the time of occurrence during practice (color scale): **Pacer Group Subject 5***



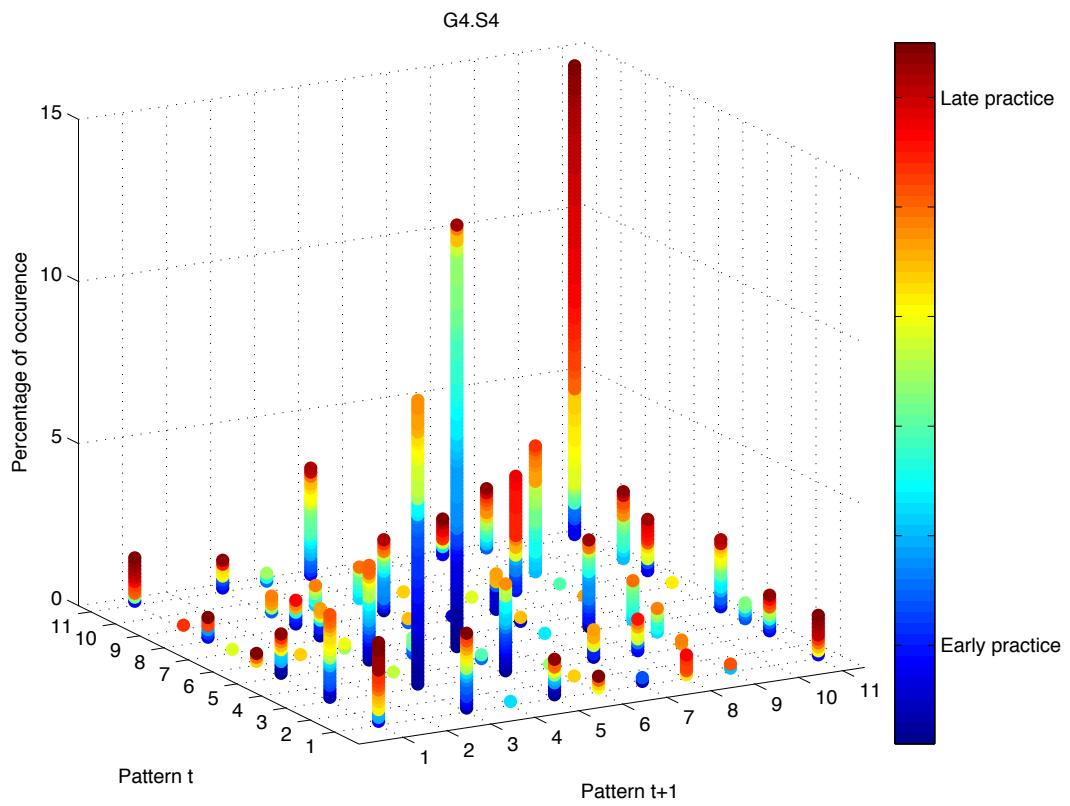
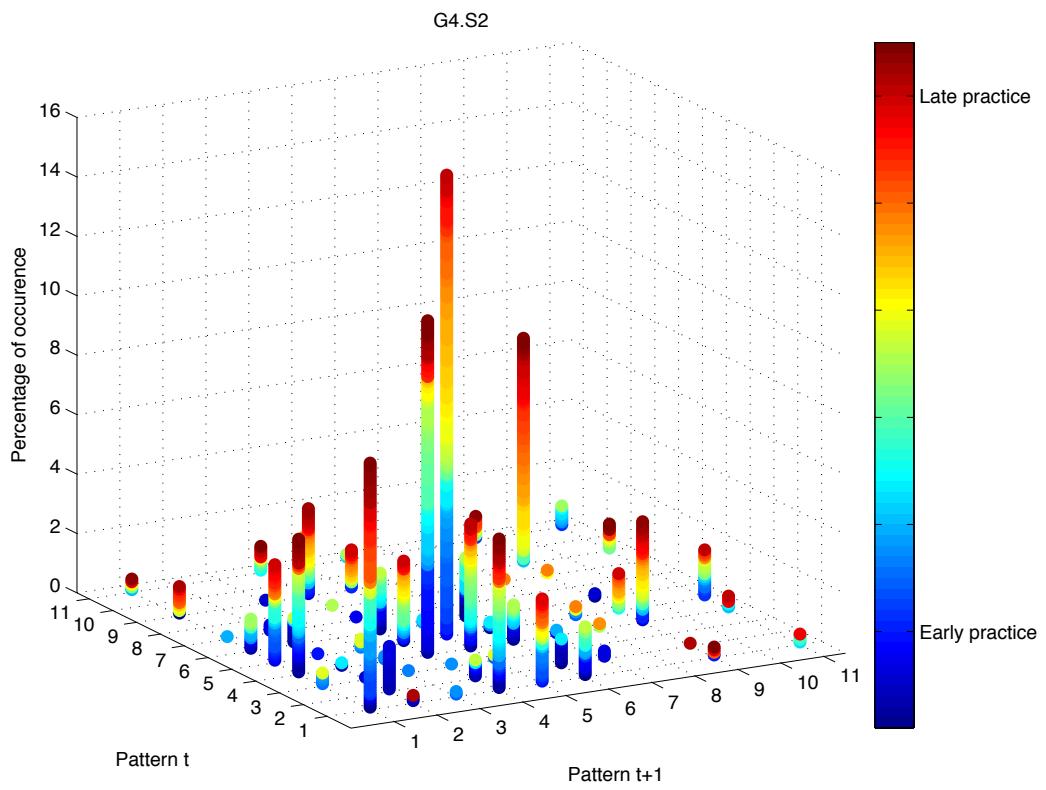
*Percentage of occurrence of transitions between cluster t (y-axis) and cluster $t + 1$ (x-axis) with regards to the time of occurrence during practice (color scale): **Pacer Group Subject 6***

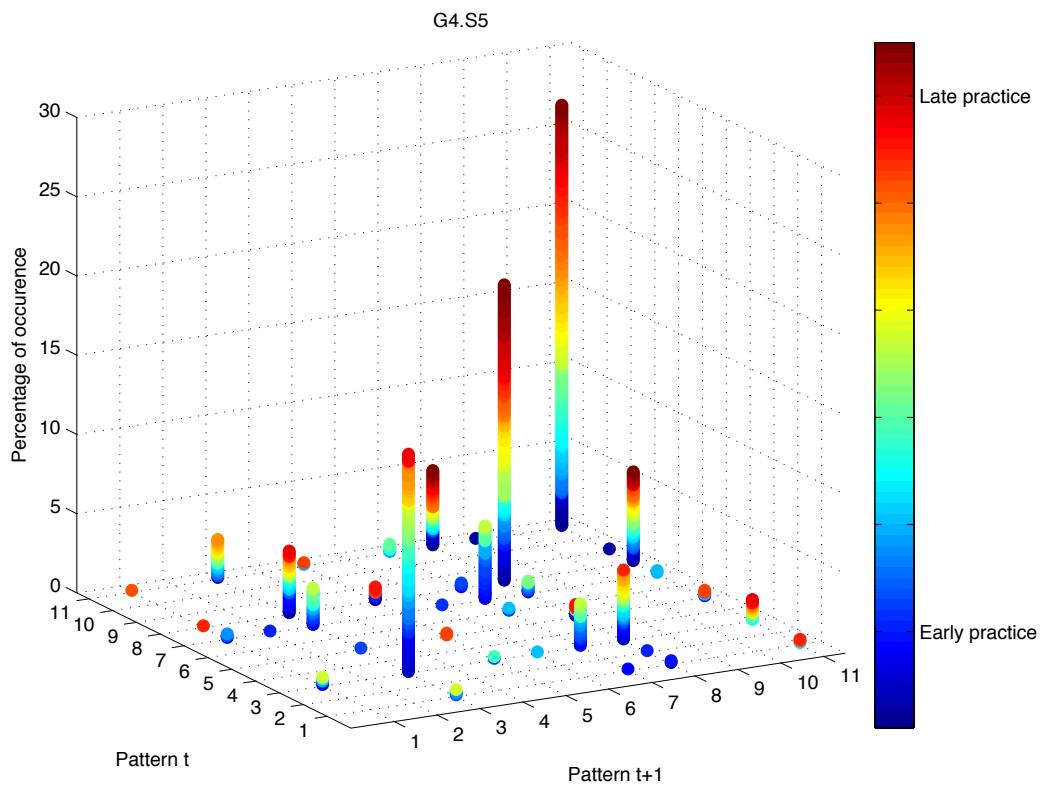


Percentage of occurrence of transitions between cluster t (y-axis) and cluster $t+1$ (x-axis) with regards to the time of occurrence during practice (color scale): Pacer Group Subject 7

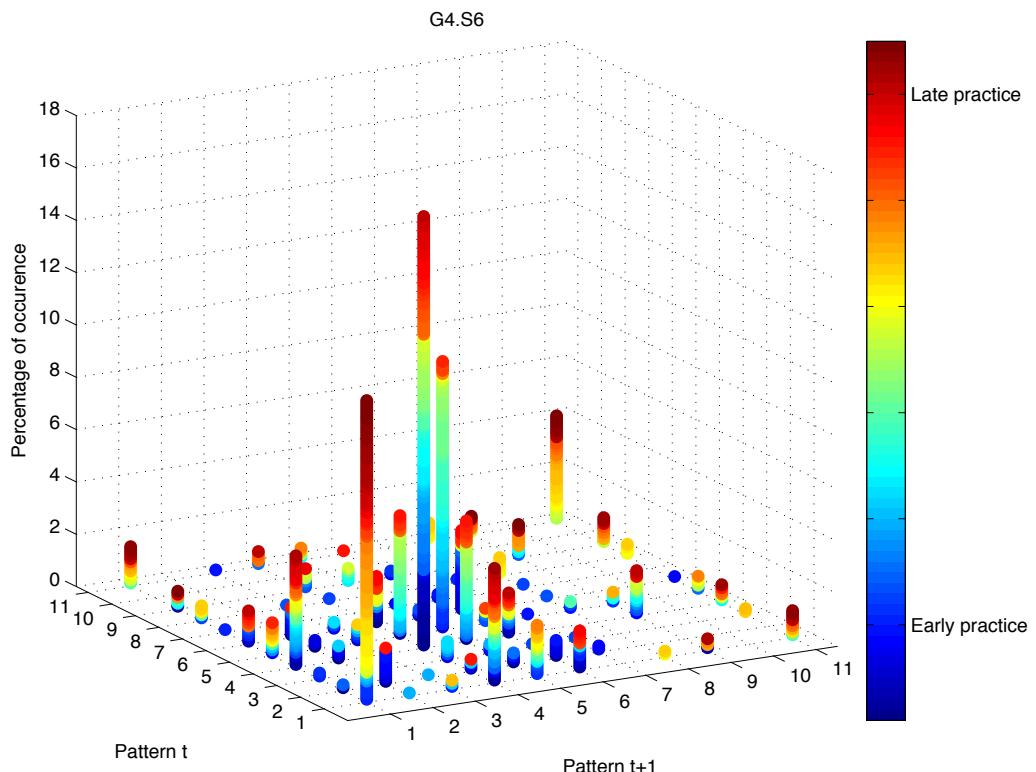


Percentage of occurrence of transitions between cluster t (y-axis) and cluster $t+1$ (x-axis) with regards to the time of occurrence during practice (color scale): Pacer Group Subject 8

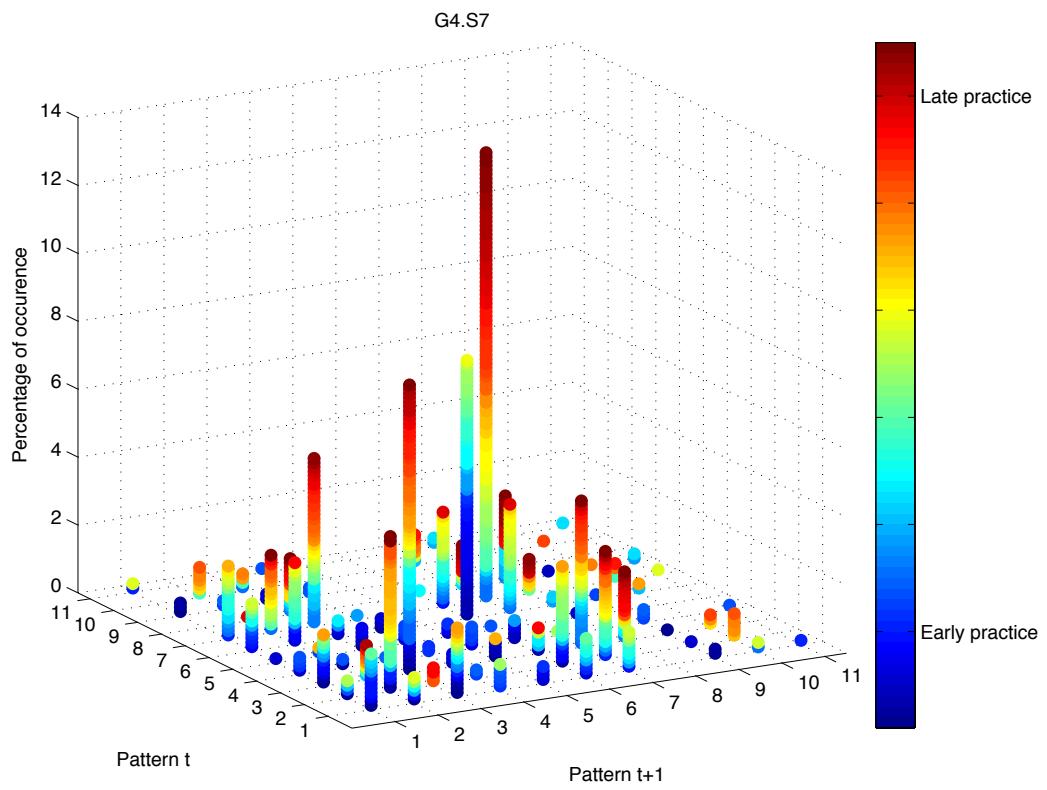




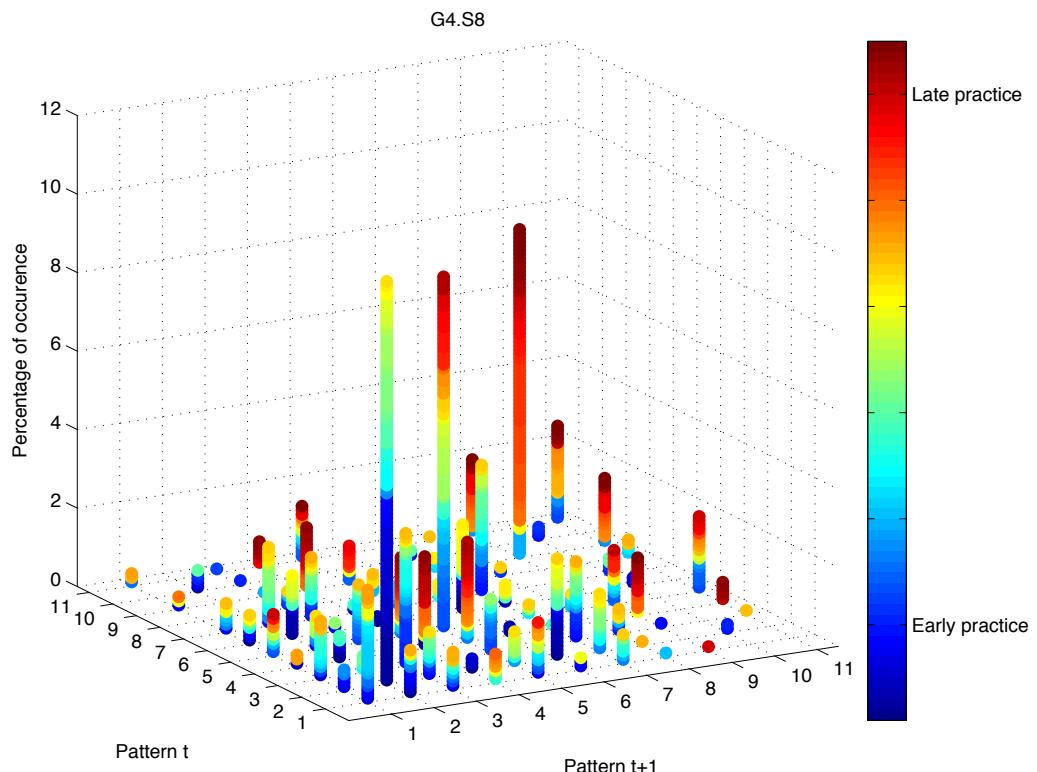
*Percentage of occurrence of transitions between cluster t (y-axis) and cluster $t + 1$ (x-axis) with regards to the time of occurrence during practice (color scale): **Prescription Group Subject 5***



*Percentage of occurrence of transitions between cluster t (y-axis) and cluster $t + 1$ (x-axis) with regards to the time of occurrence during practice (color scale): **Prescription Group Subject 6***



*Percentage of occurrence of transitions between cluster t (y-axis) and cluster $t + 1$ (x-axis) with regards to the time of occurrence during practice (color scale): **Prescription Group Subject 7***



*Percentage of occurrence of transitions between cluster t (y-axis) and cluster $t + 1$ (x-axis) with regards to the time of occurrence during practice (color scale): **Prescription Group Subject 8***